

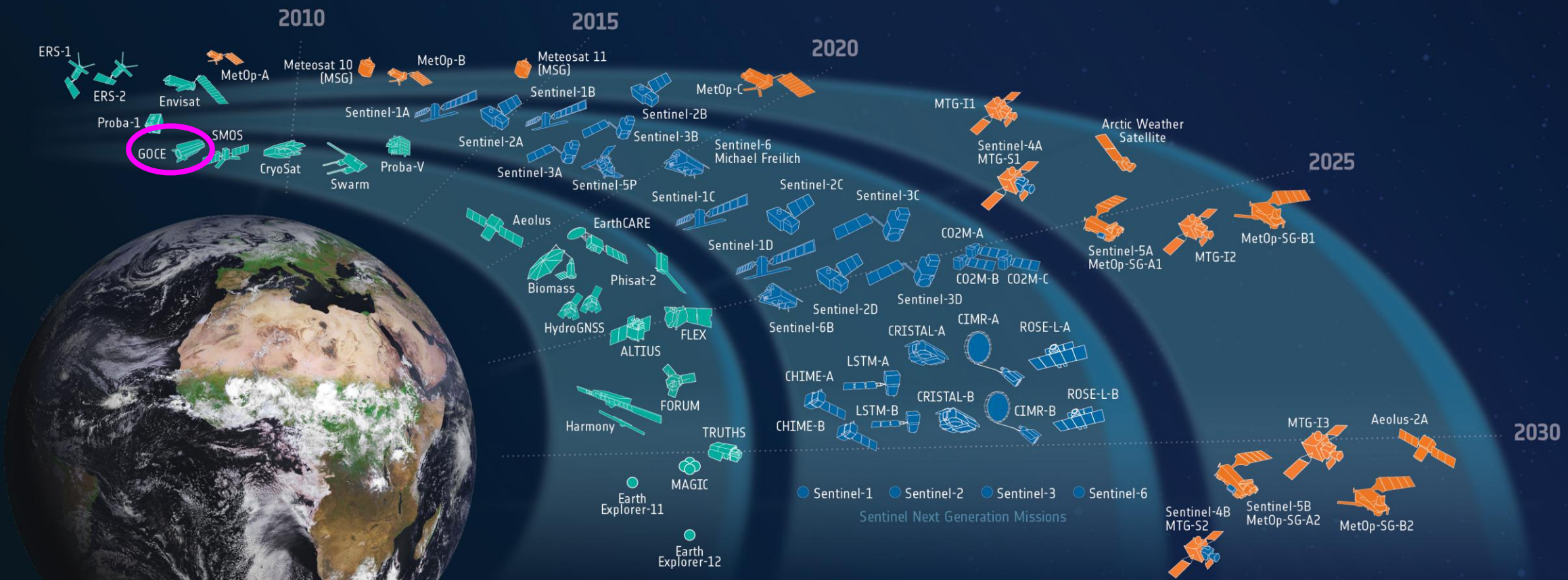
Radiative transfer

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ISMAR-CNR

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Mission 4 “Education and Research” - Component 2: “From research to business” - Investment
3.1: “Fund for the realisation of an integrated system of research and innovation infrastructures”



What do we really measure with Satellite Remote Sensing?



Science 
Copernicus 
Meteorology 

INVERSION OF THE REMOTELY SENSED SIGNAL

The measured radiation L can be considered as a vector in a multidimensional space:

$$L = f \left[\lambda, s_{x,y,z}, t, (\theta_s, \theta_v, \varphi), (I, Q, U, V) \right]$$

where

λ = wavelength

$s_{x,y,z}$ = x, y, z position in the space (e.g. in the image)

t = time

$\theta_s, \theta_v, \varphi$ = set of angles that define the observation-illumination geometry (i.e the path: radiation source-observed object-instrument)

I, Q, U, V = Polarization of the measured radiation

Radiative Transfer: What is it?

Radiative Transfer \approx Elettromagnetis

But....

We need to build a bridge which would connect the mainland of physics with the tiny island of radiative transfer and he said well, unfortunately, he had a prediction even if this bridge were to be built there would be very little traffic two tries for two reasons.

The physicists are not so much interested in the subject.

...the happy Arbor Regents on this island are happy because they're happy already so they don't feel in it physics to become happier.

Michael Mishchenko Maniac Lecture, January 26, 2015

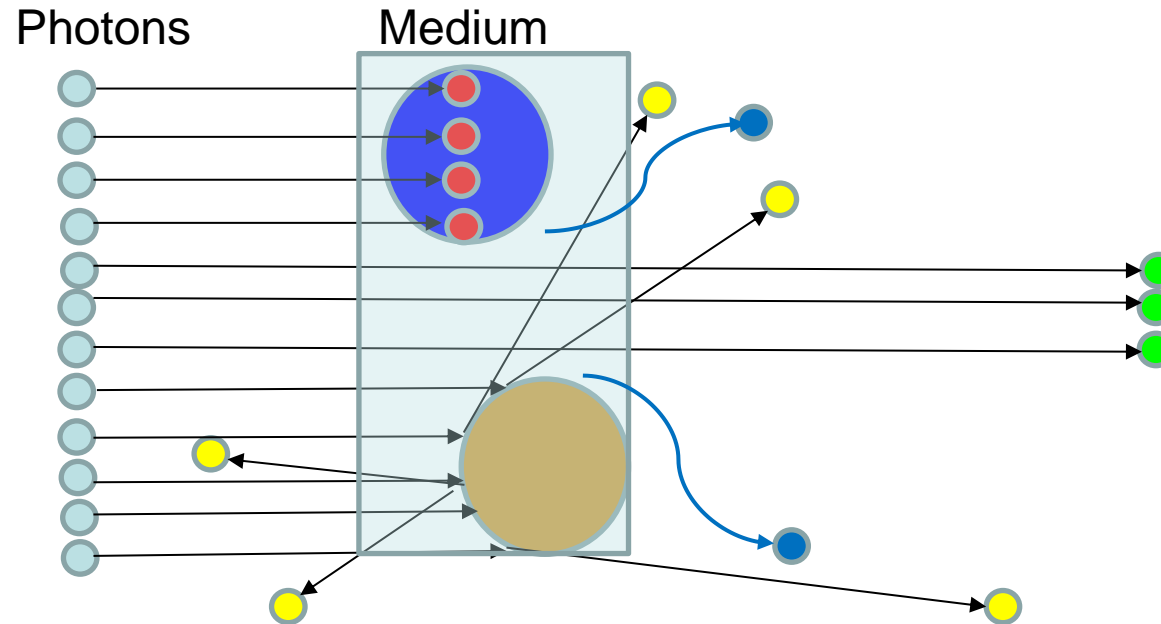
www.youtube.com/watch?v=hjKJyn_uoIE (~ 27:00)

Radiative Transfer: What is it?

Photons (=e.m. wave) propagating accross a medium (atmosphere, surface) can:

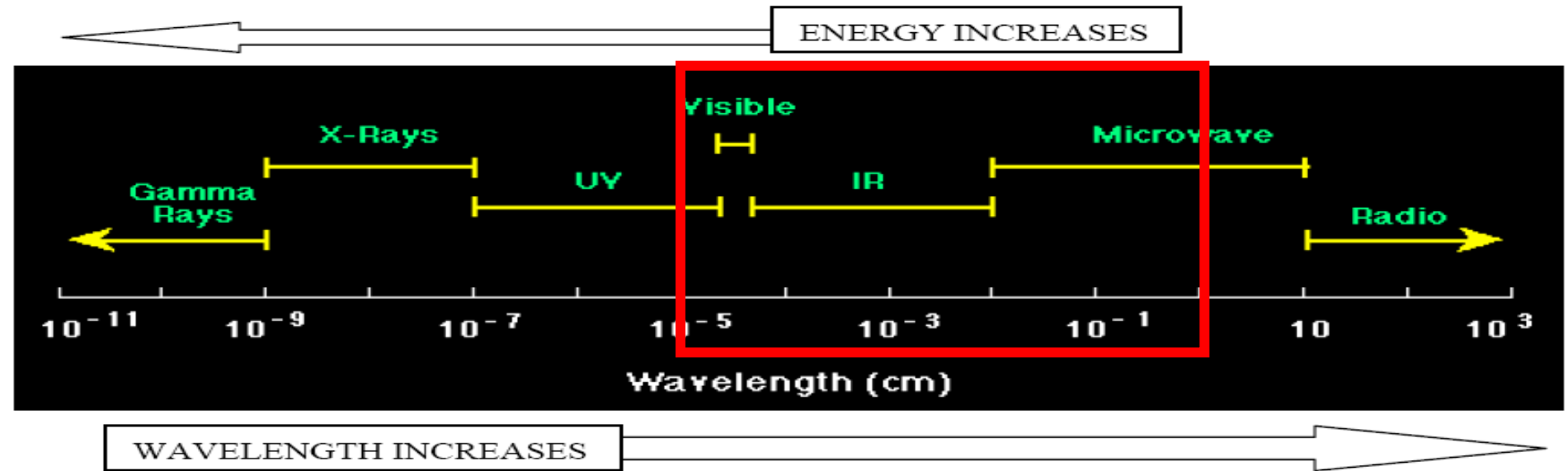
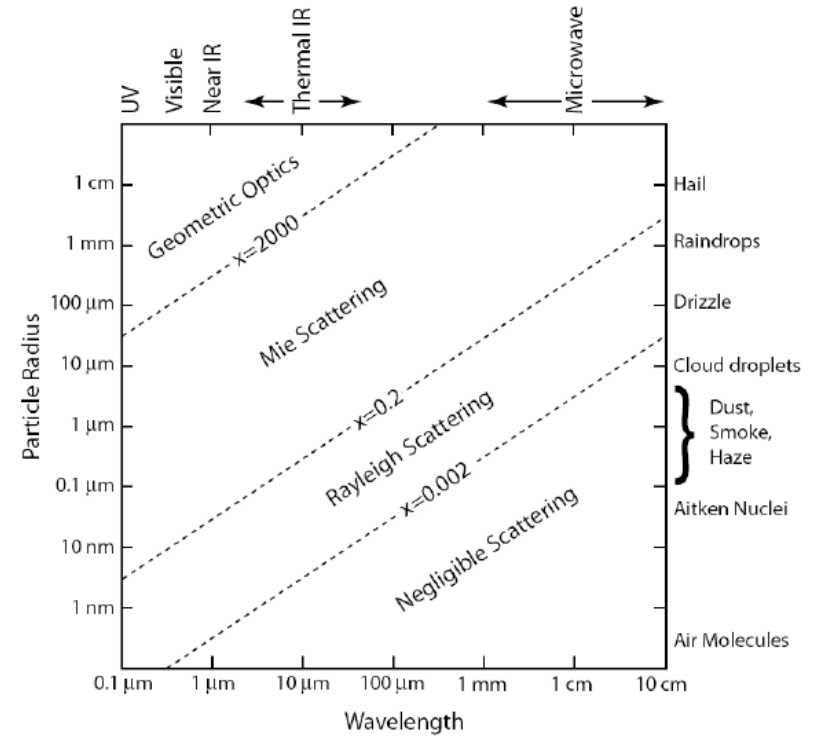
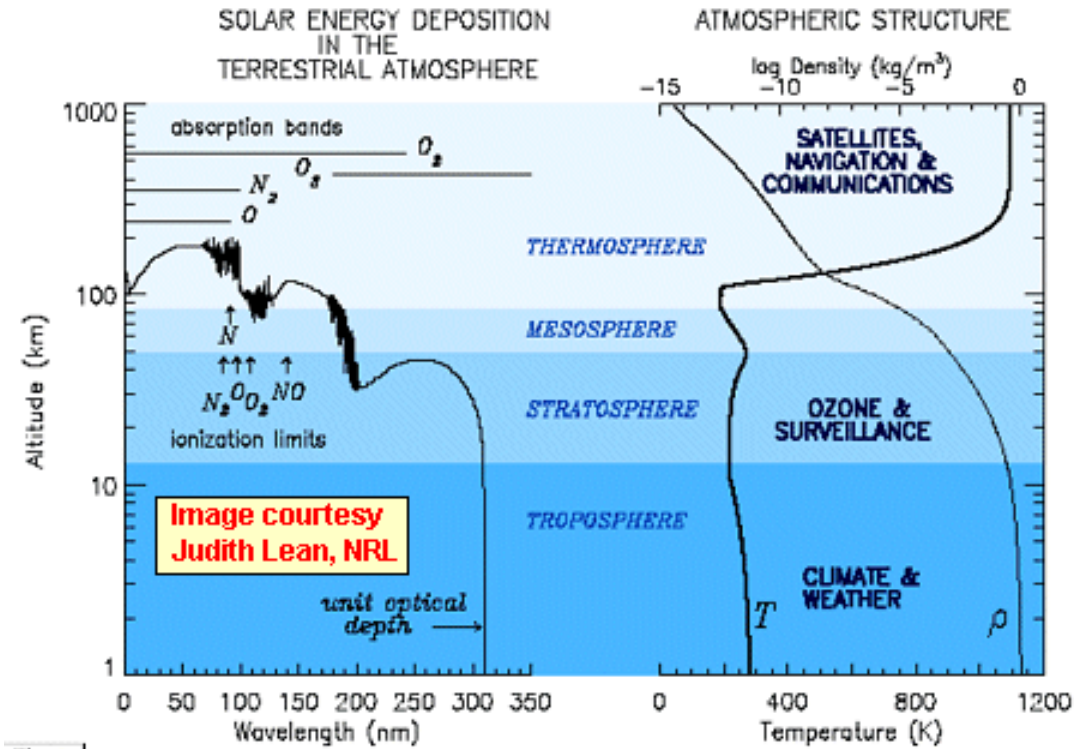
- Propagate without interacting with the medium → **transmission** (*glass*)
- Have an elastic interaction: i.e. change of dirrection of propagation (and polarization status) → **reflection/diffusion/scattering** (*mirror*)
- Exchange the energy with the medium → **absorption** (*black surface*)

In addition the medium can generate photons → **emission**



Radiative Transfer: branch of the physics that studies the interaction between e.m. radiation and atmosphere & surfaces. Main applications: Radioan budget estimation, Remote sensing

Useful range for earth atmosphere remote sensing



Relevant Radiative Interaction processes

- Molecular Absorption
- Absorption associated with scattering and reflection
- Scattering*
- (Surface) Reflection*
- Atmospheric Bending (in Radio occultation)*
- Thermal emission (LTE e NLTE)
- Others (Stimulated emissions, Fluorescence, Raman scattering)

* Elastic and Polarizing processes

Molecular (Gas) Absorption

It depends from:

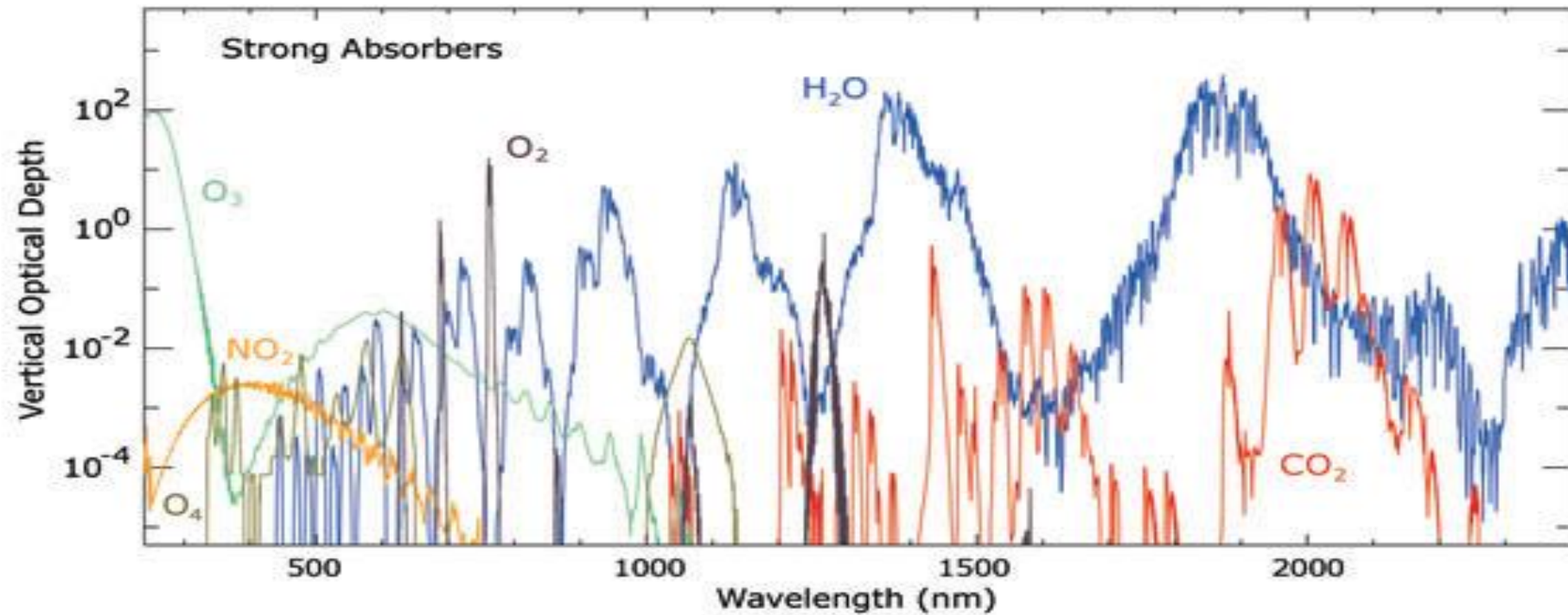
- Characteristics of the molecules (i.e. composition of the atmosphere)
- Wavelength
- Temperature and pressure of the gas.

It is represented with:

- wavelength dependent absorption cross section*

* It can be estimated with different methods depending mostly from the spectral resolution of the application: e.g. line-by-line, band models, emissivity models. <https://hitran.org/>

Example of gas absorption spectra in the solar (UV/VIS/SWIR) range



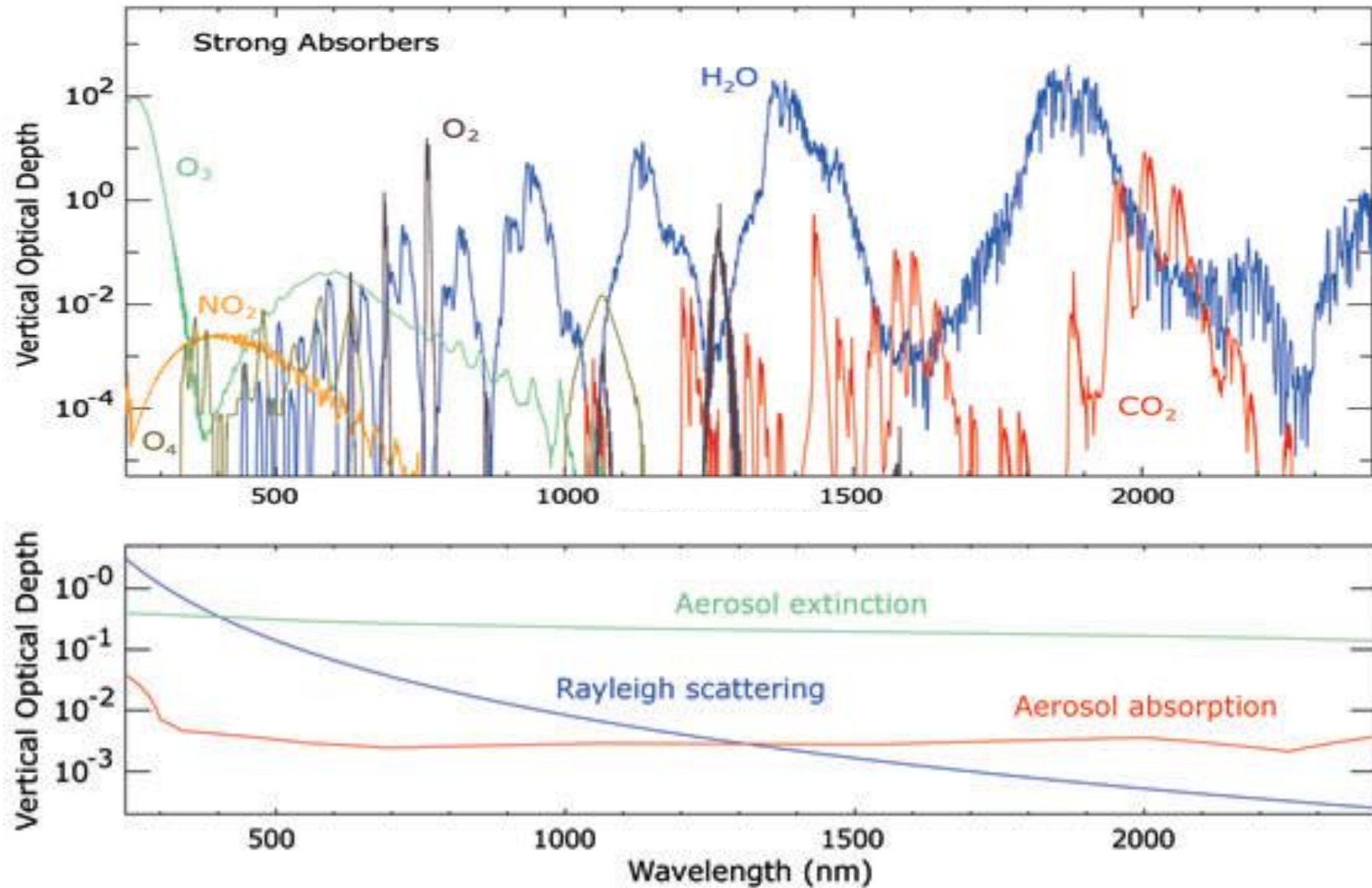
Atmospheric (Gas/Aerosols/Clouds) Scattering

It depends from:

- Composition of the scatterer
- Wavelength
- Dimensions, shape and orientation of the scatterer

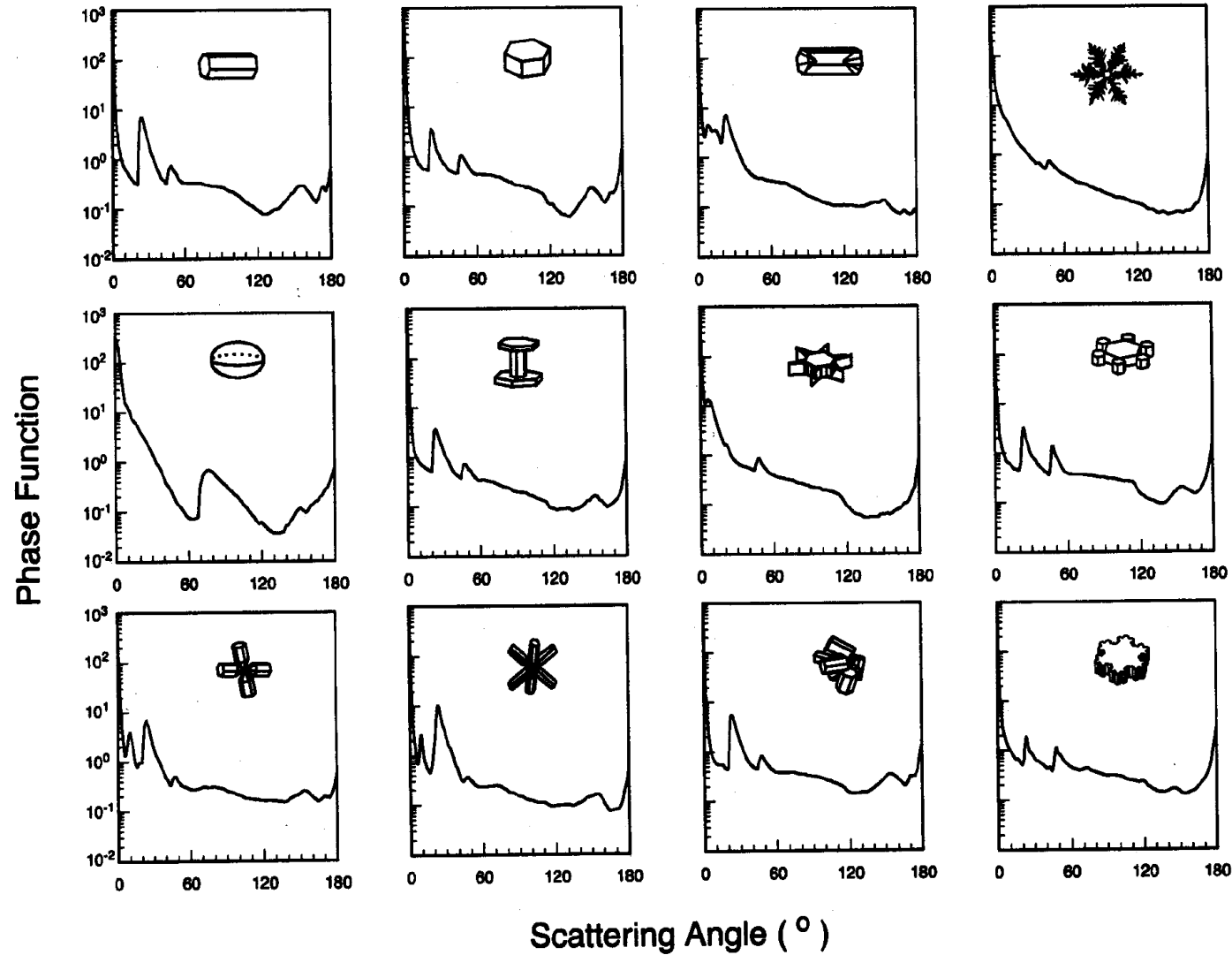
It is represented with:

- wavelength dependent absorption cross section
- wavelength dependent scattering cross section
- a 4x4 matrix of wavelength & angularly dependent functions giving the probability of changes in propagation and polarization properties

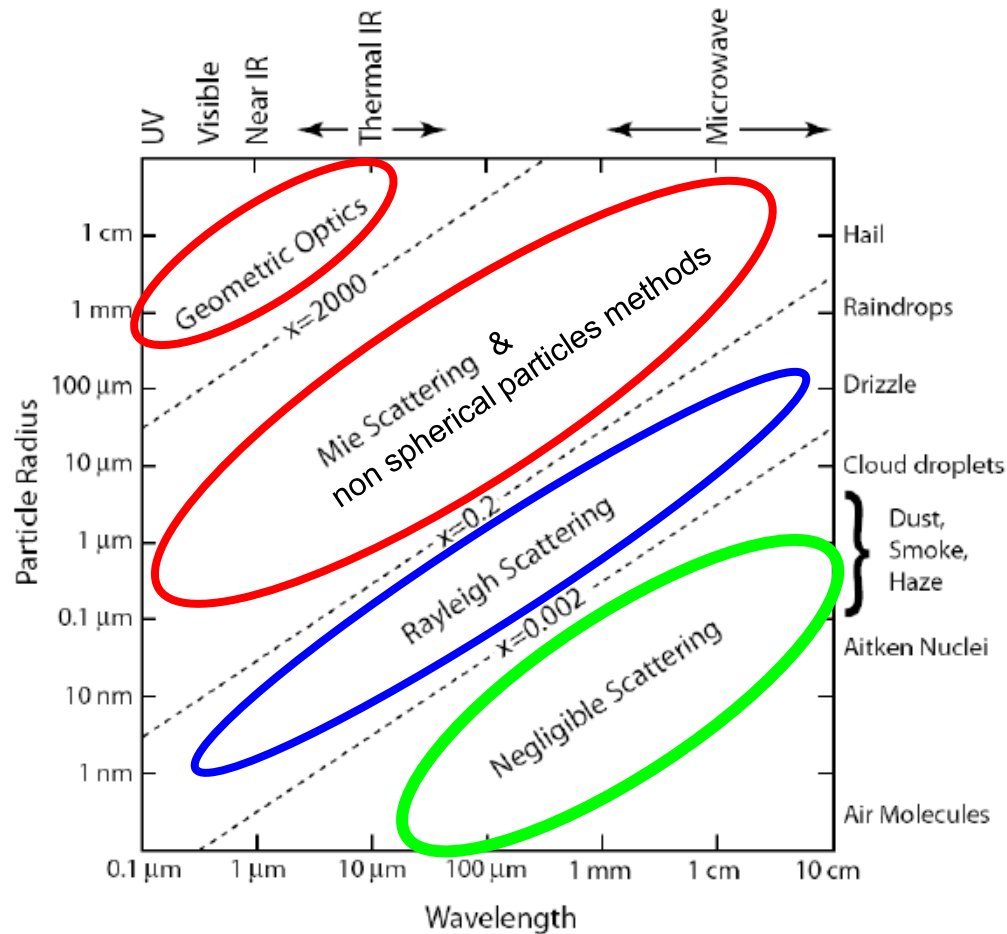


Examples of gas absorption spectra (upper panel) and scattering extinction (lower panel) in the solar (UV/VIS/SWIR) range: **scattering spectral dependence smoother than gas absorption one**

Examples of phase functions (probability of having a photon scattered in a given direction (scattering angle) for different type of cloud ice particles



Numerical methods for computations of single scattering properties



Mie scattering & Geometric Optics:

Depends from scattering particle amount, shape, dimension & relative orientation particle-wave

Rayleigh scattering:

Depends from scattering particle amount

Negligible Scattering:

independent from an particle property

Surface Reflection

It depends from:

- Composition of the surface
- Wavelength
- Dimensions, shape and orientation of the surface components

It is represented with:

- wavelength & angularly dependent functions giving the probability of changes in propagation and polarization properties. NB in general the composition dependent component have a

Geometrical dependence of reflectance

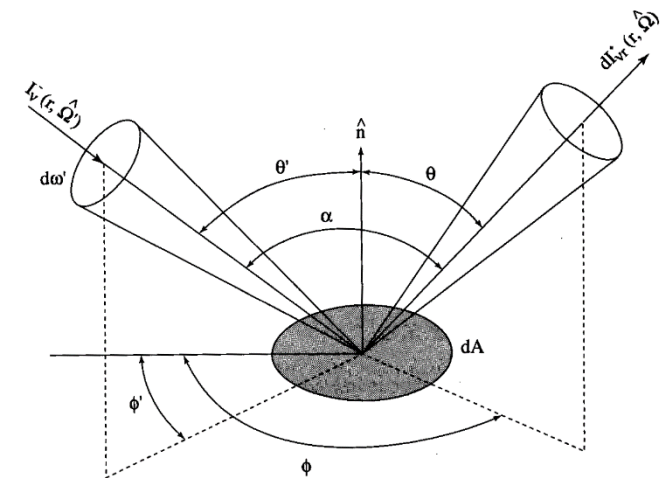
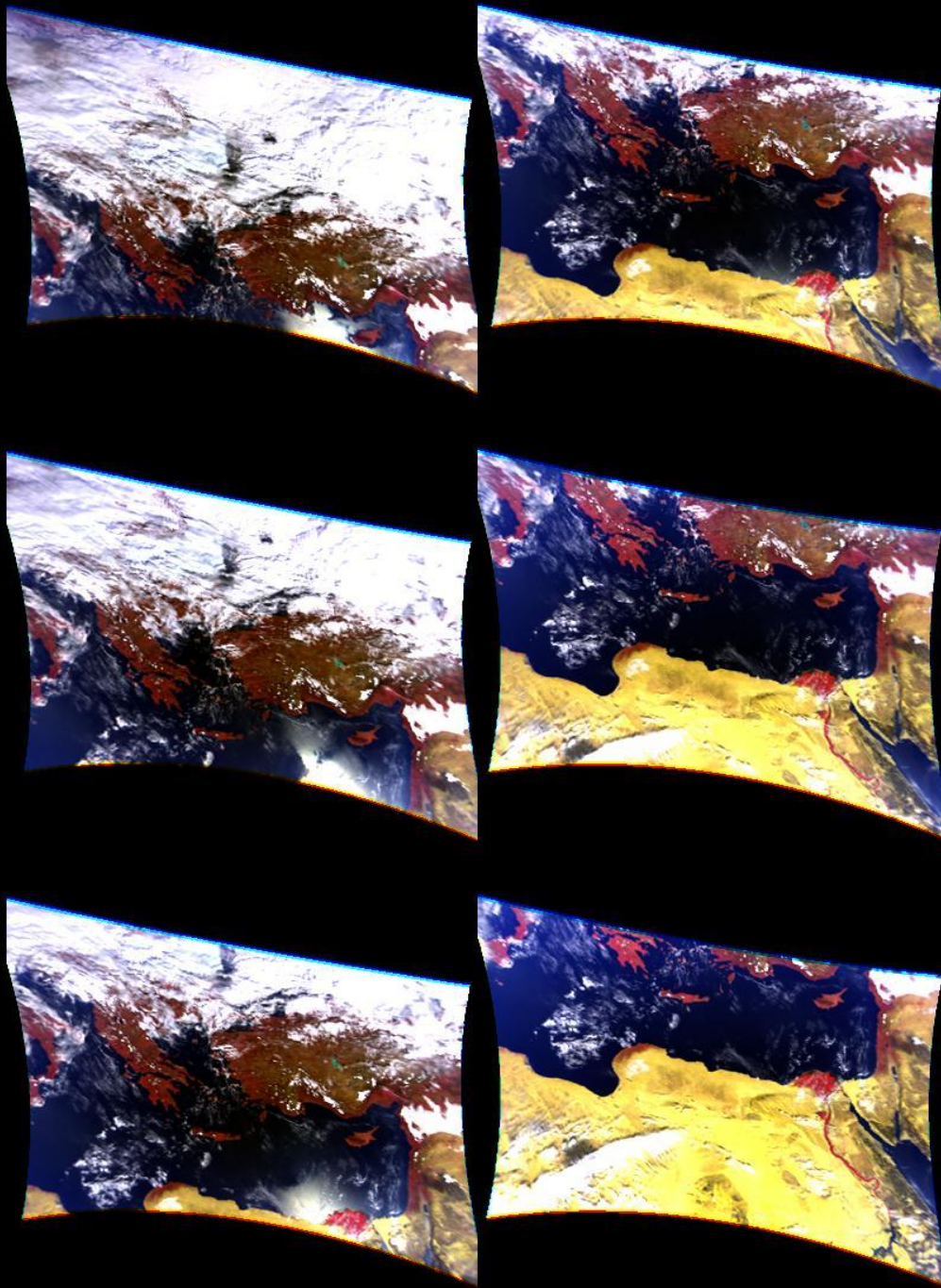


Figure 5.1 Geometry and symbols for the definition of the BRDF. The angle α is the backscattering angle.

Surface reflectance geometry

Several possible definitions depending on the definitions of:

- the incident radiation source: point (e.g. sun) or diffuse (e.g, atmospheric thermal emission)
- the reflected radiation *observer*: point (e.g. instrument) or diffuse (e.g, semi hemisphere)

In case of remote sensing from satellite (point observer) of solar radiation (point source) we have:

BRDF: Bidirectional Reflectance Distribution Function

BPDF: Bidirectional Polarization Distribution Function

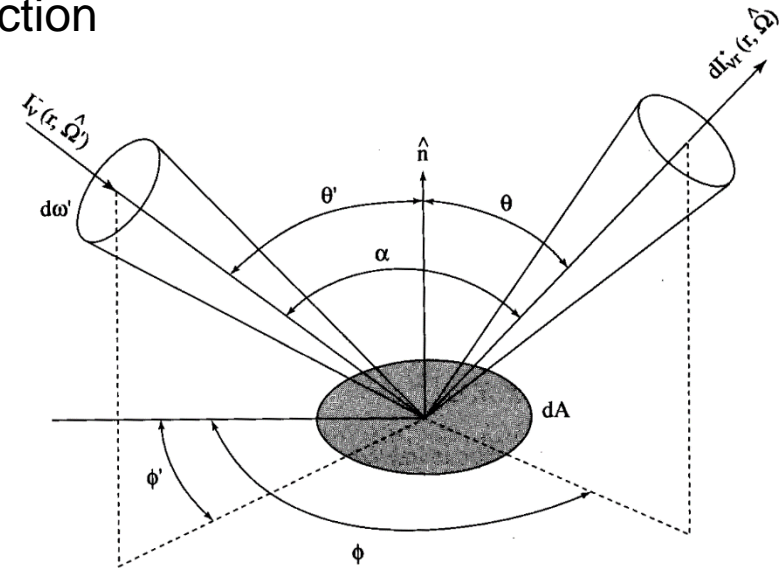
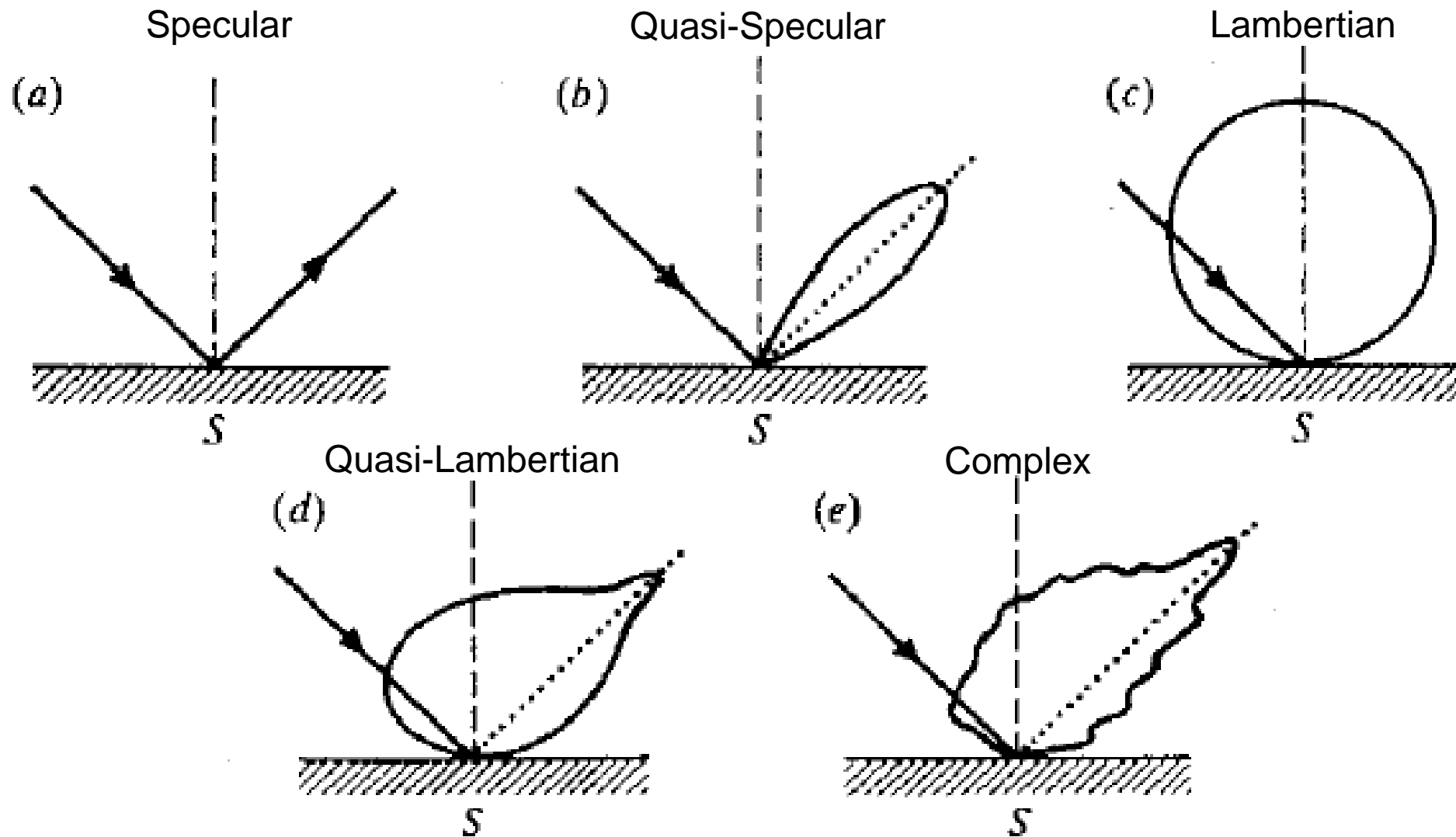


Figure 5.1 Geometry and symbols for the definition of the BRDF. The angle α is the backscattering angle.

Simple geometrical model for reflection



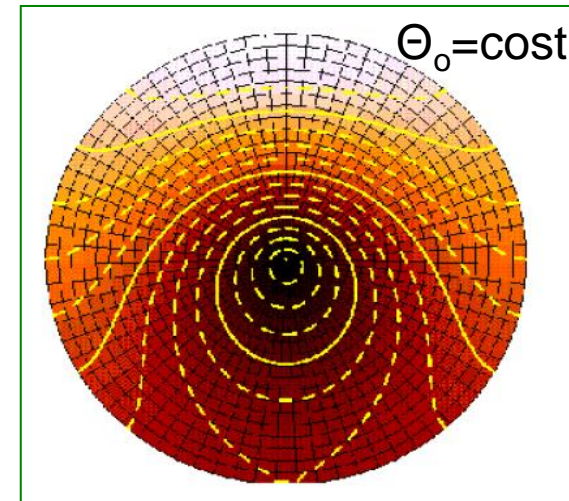
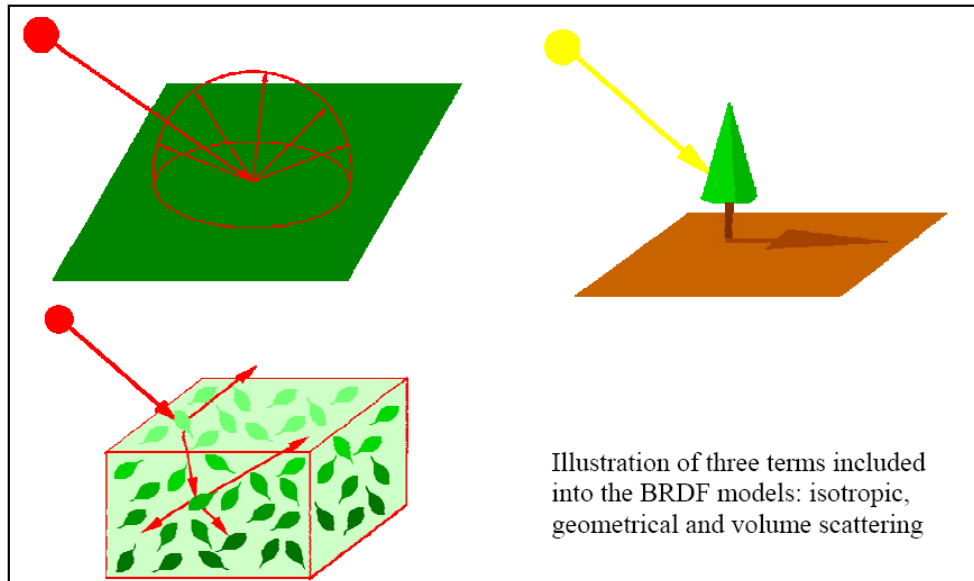
Fresnel Equations

en.wikipedia.org/wiki/Fresnel_equations

$$|R_r|^2 = \frac{(\sin \gamma - u)^2 + v^2}{(\sin \gamma + u)^2 + v^2},$$

$$|R_l|^2 = \frac{[(n_r^2 - n_i^2) \sin \gamma - u]^2 + (2n_r n_i \sin \gamma - v)^2}{[(n_r^2 - n_i^2) \sin \gamma + u]^2 + (2n_r n_i \sin \gamma + v)^2}, \quad (2.10)$$

$$u = \left\{ \frac{n_r^2 - n_i^2 - \cos^2 \gamma + [(n_r^2 - n_i^2 - \cos^2 \gamma)^2 + 4n_r^2 n_i^2]^{1/2}}{2} \right\}^{1/2},$$
$$v = \left\{ \frac{-(n_r^2 - n_i^2 - \cos^2 \gamma) + [(n_r^2 - n_i^2 - \cos^2 \gamma)^2 + 4n_r^2 n_i^2]^{1/2}}{2} \right\}^{1/2}.$$



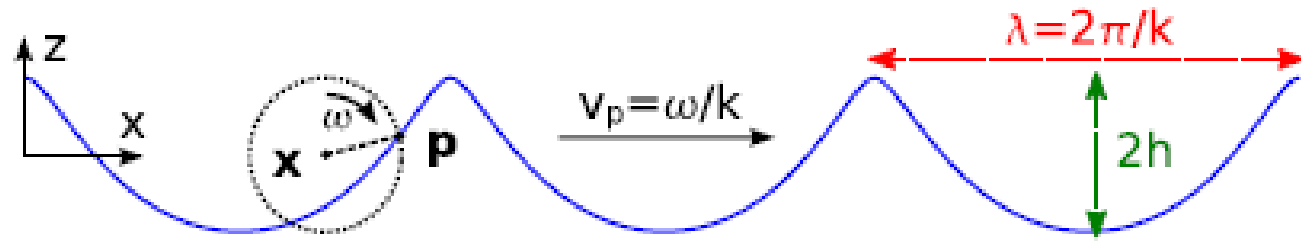
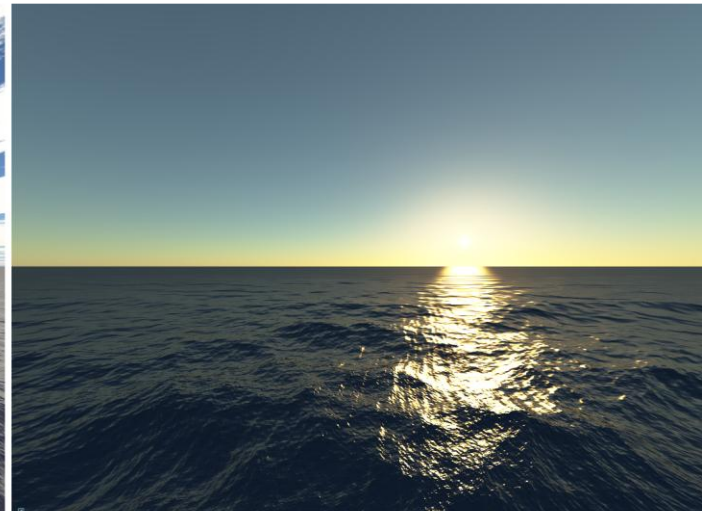
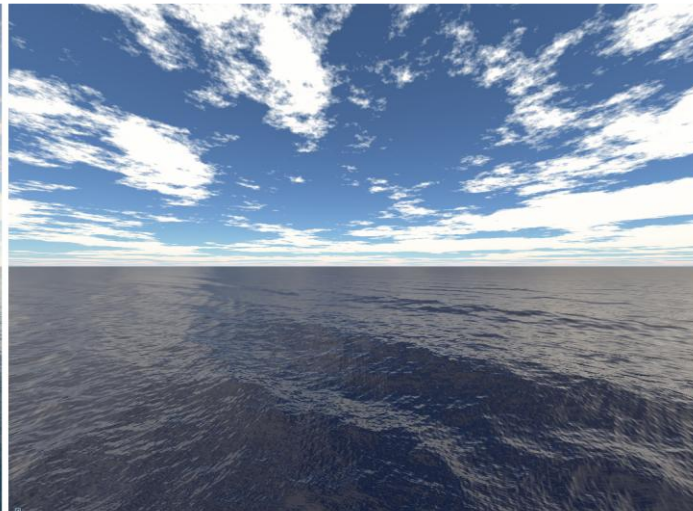
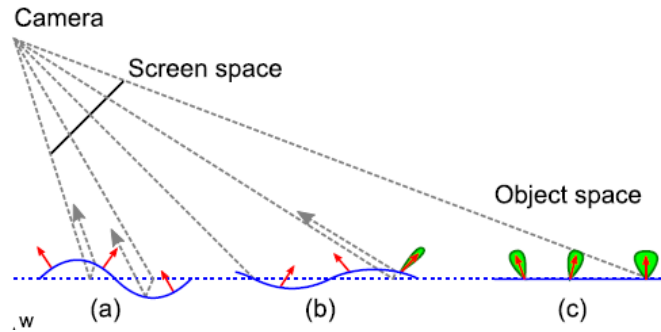


Figure 2: Trochoid waves. A Gerstner wave is defined by $\mathbf{p} = [x + h \sin(\omega t - kx), h \cos(\omega t - kx)]^T$, where $\omega = \sqrt{gk}$.



<https://www.disneyanimation.com/open-source/>
<https://www.youtube.com/watch?v=Zcp2ciQLHpQ>



BRDF Explorer

File Utilities Help

Theta H

PhIV

51.12 Lock

Theta H Theta D Theta V Albedo

3D Plot

Lit Object

IBL: IBL IS Keep Sampling

Gamma 2.2

Exposure 0

Image Slice Lit Object

BRDF Parameters

Luminance

Log plot: $y = \log_{10}(x + 1.0)$

Multiply by N · L

Incident angle - thetaL 45

Incident angle - phiL 45

white-marble.binary

Visible

ashikhman_shirley.brdf

Visible

Rs 0.023

Rd 0.195

nu 100

Lit Sphere

Double theta Multiply by N · L

Gamma 2.2

Exposure 0

Polar Plot

Estimation with measurements+semiempirical models

$$\rho(\theta_1, \phi_1; \theta_2, \phi_2) = \frac{\omega}{4} \frac{1}{\mu_1 + \mu_2} \{ [1 + B(g)] P(g) + H(\mu_1)H(\mu_2) - 1 \} \quad (1)$$

where

$$\mu_1 = \cos \theta_1$$

$$\mu_2 = \cos \theta_2$$

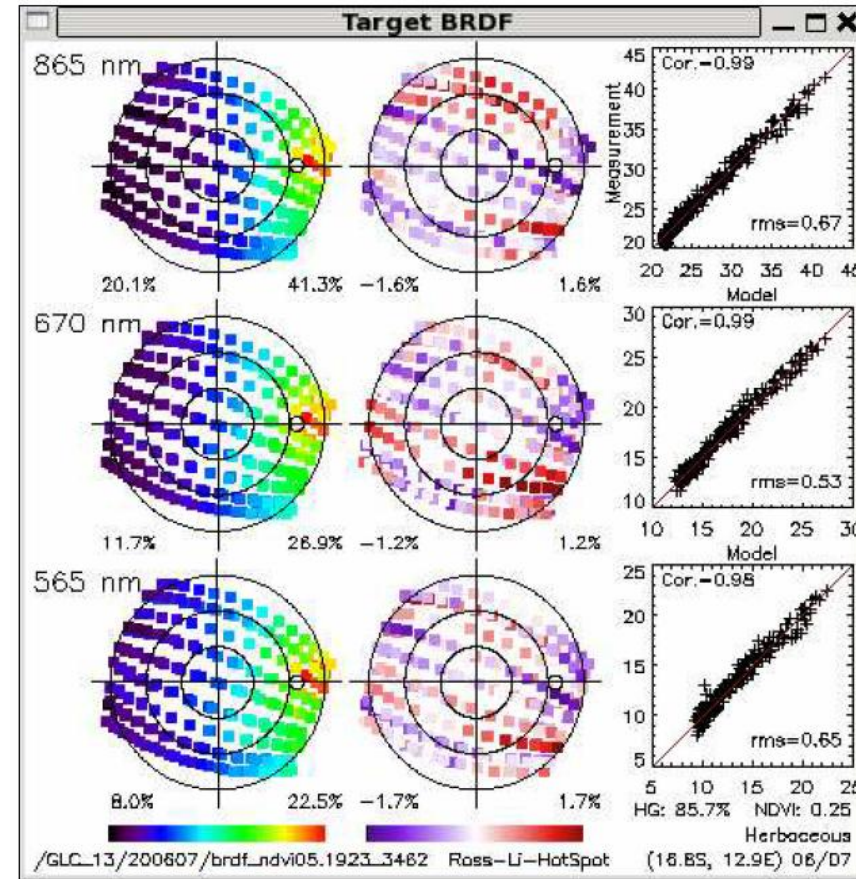
$$\cos g = \cos \theta_1 \cos \theta_2 + \sin \theta_1 \sin \theta_2 \cos (\phi_1 - \phi_2)$$

$$B(g) = \frac{B_0}{[1 + (1/h) \tan (g/2)]}$$

$$B_0 = \frac{S_H(0)}{\omega P(0)}$$

$$H(x) = \frac{1 + 2x}{1 + 2(1 - \omega)^{1/2}x}$$

Reflectance measurements (left column), the difference with the modeling (center column) and the measurement-model scatter plot (right column). It is possible to display other representations of measurements through the main command window (display options).



Considerations about BRDF (and BPDF)

$$\text{BRDF}(\lambda, \vartheta_s, \vartheta_v, \varphi) \approx A(\lambda) \cdot B(\lambda, \vartheta_s, \vartheta_v, \varphi)$$

- $A(\lambda)$: depends from the material
- $B(\lambda, \vartheta_s, \vartheta_v, \varphi)$ = depends from the geometry of the surface and can be considered (for a given wavelength range: e.g. Visible) independent from the wavelength

New generation of satellites tends to have for few channels multiangular observation capabilities + hyperspectral capabilities for a given geometry (e.g. PACE <https://pace.oceansciences.org/mission.htm>)

https://youtu.be/r_qNAhJXaXU

Surface Thermal Emission

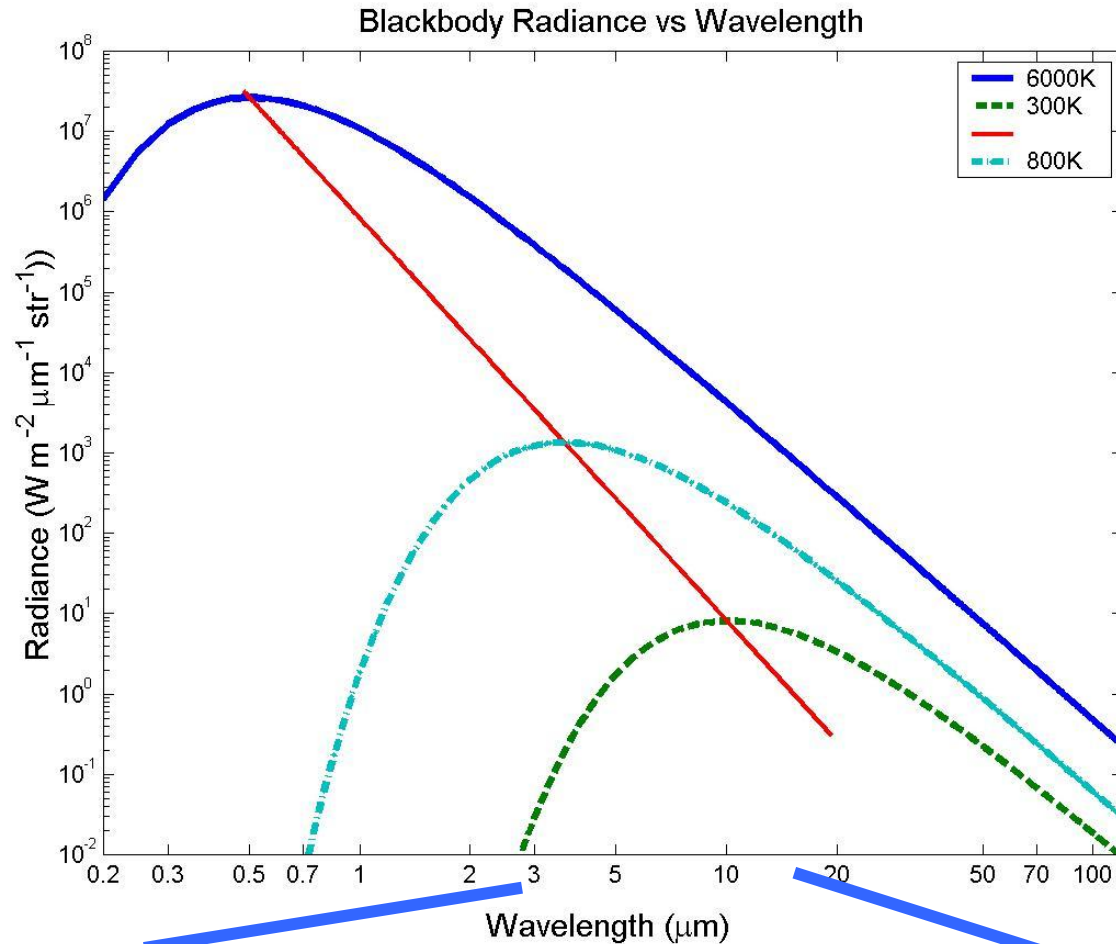
It depends from:

- Composition of the surface
- Wavelength

It is represented with:

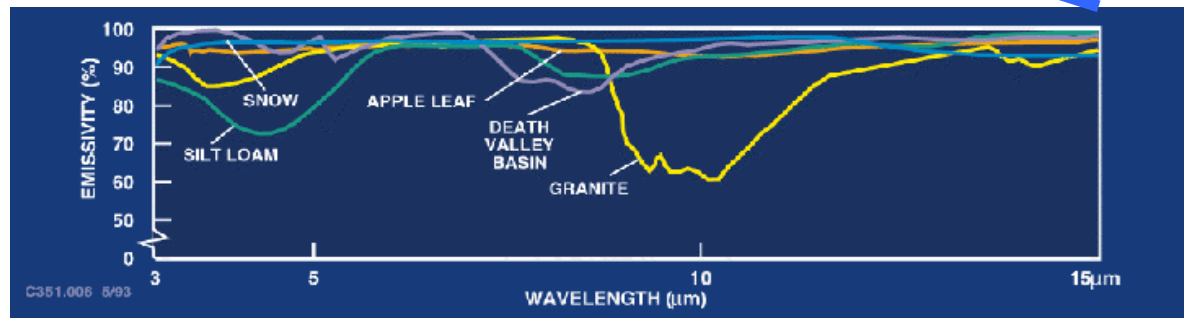
- wavelength & dependent variable emissivity $[0,1]$ that represent the ratio between the radiative behavior of the material and the ideal black body (0=mirror, 1=blackbody)

Thermal Emission

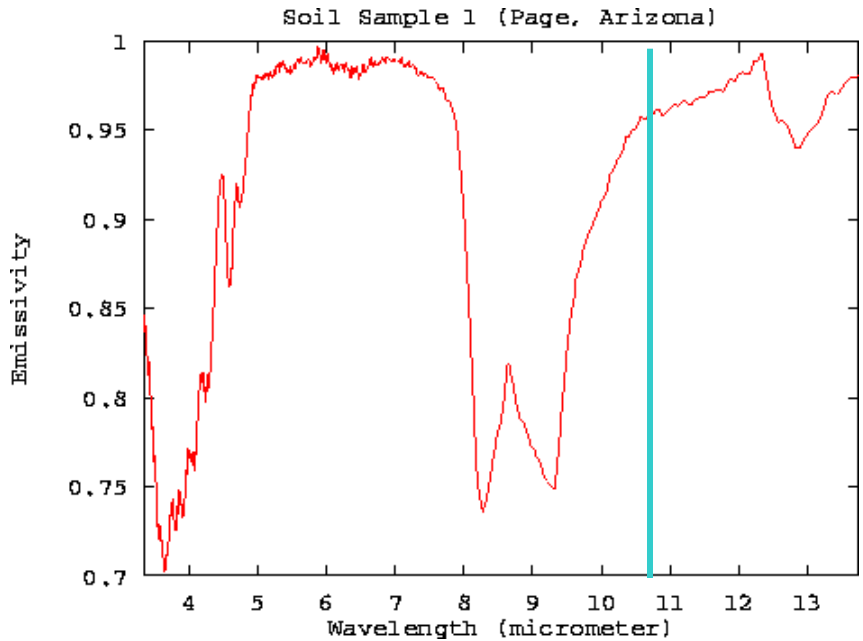
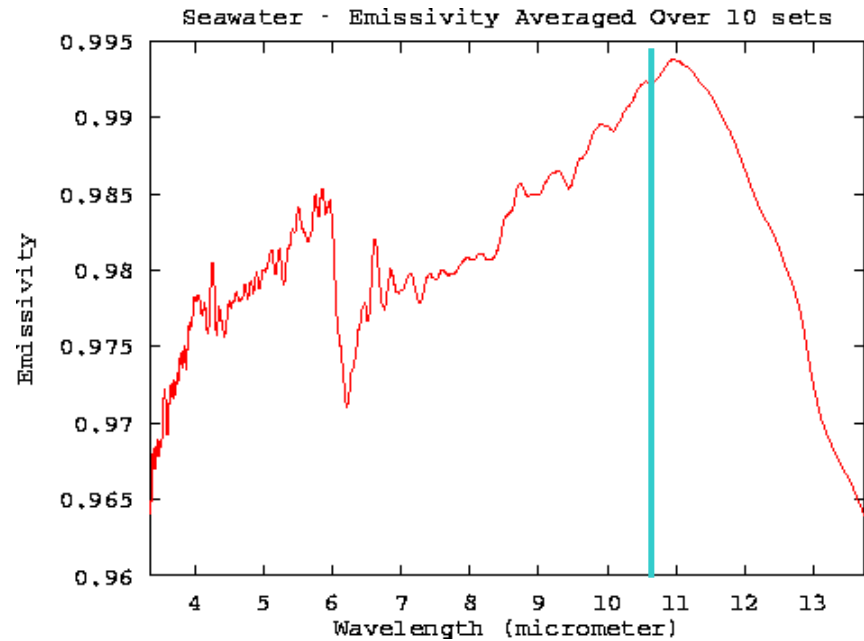
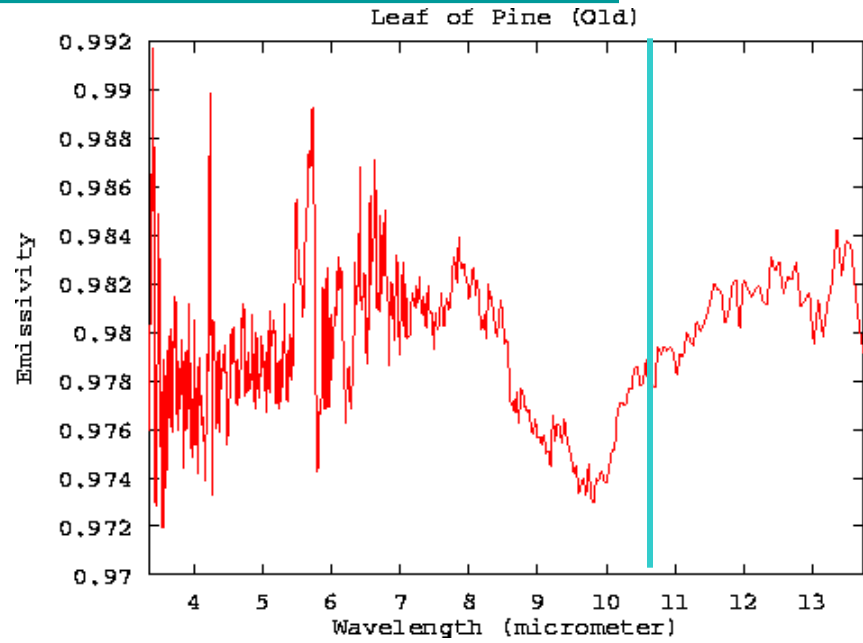
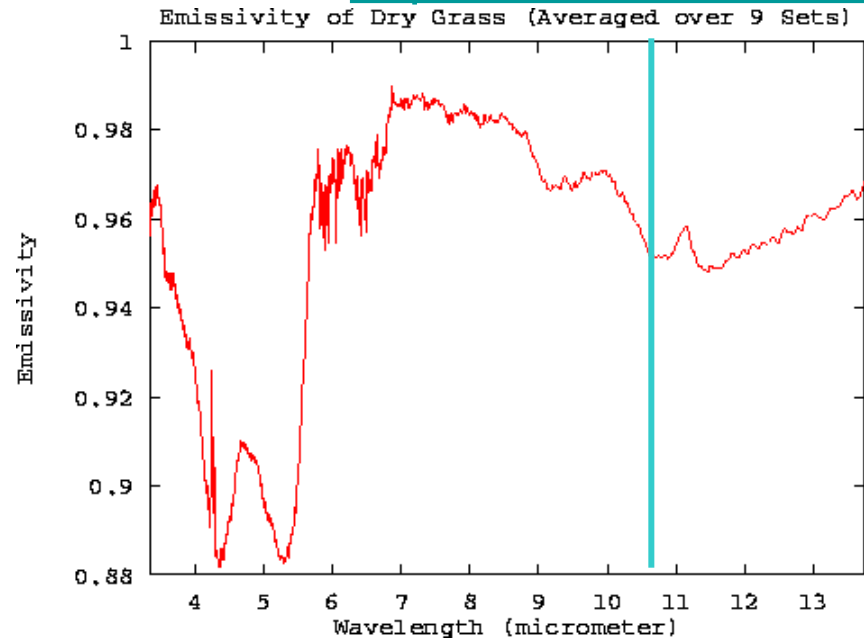


Any volume of matter at absolute temperature $> 0 \text{ K}$ emits radiation as a function of:

-its temperature and wavelength (Planck Law in Local Thermodynamic Equilibrium conditions)



- its composition (dielectric properties \rightarrow emissivity) (Kirchoff Law)



Chlorophyll fluorescence

It depends from:

- Amount of chlorophyll in the observed scene
- Wavelength
- The spectrum of exciting radiation

It is represented with:

- Spectra of chlorophyll emission efficiency

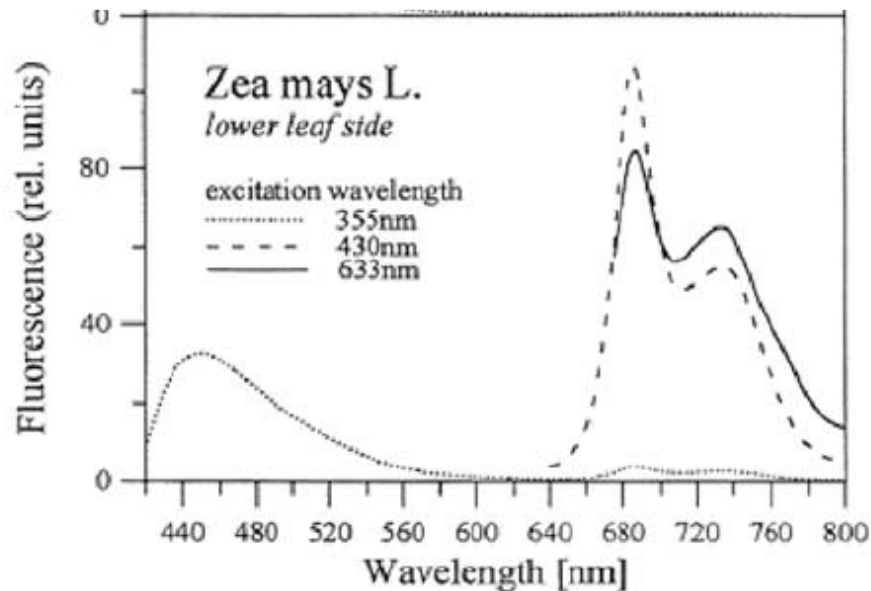
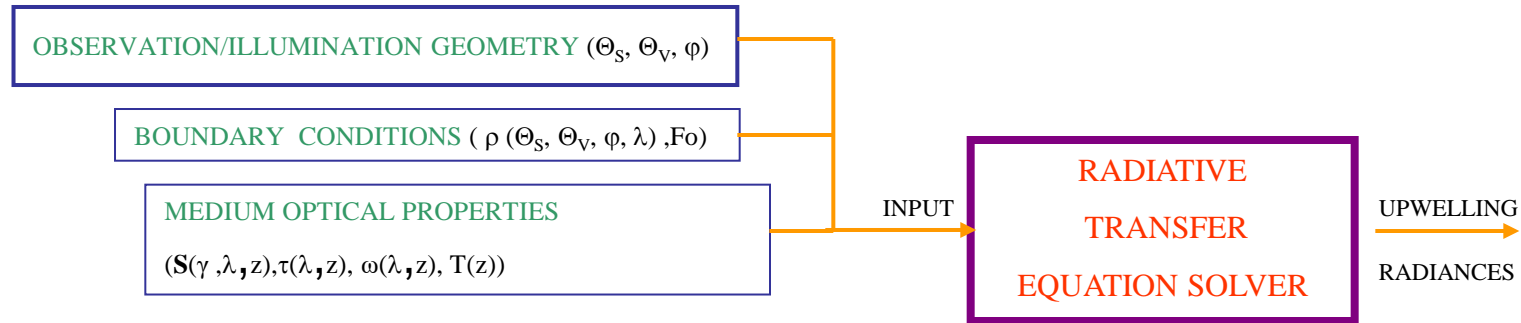


Figure 1. Fluorescence emission spectra of the upper and lower leaf side of a full-grown maize leaf (chlorophyll content $33.2 \mu\text{g cm}^{-2}$). The chlorophyll fluorescence yield is much higher for excitation at 430 nm and 633 nm than by UV radiation (355 nm) [Lichtenthaler et al., 1998].

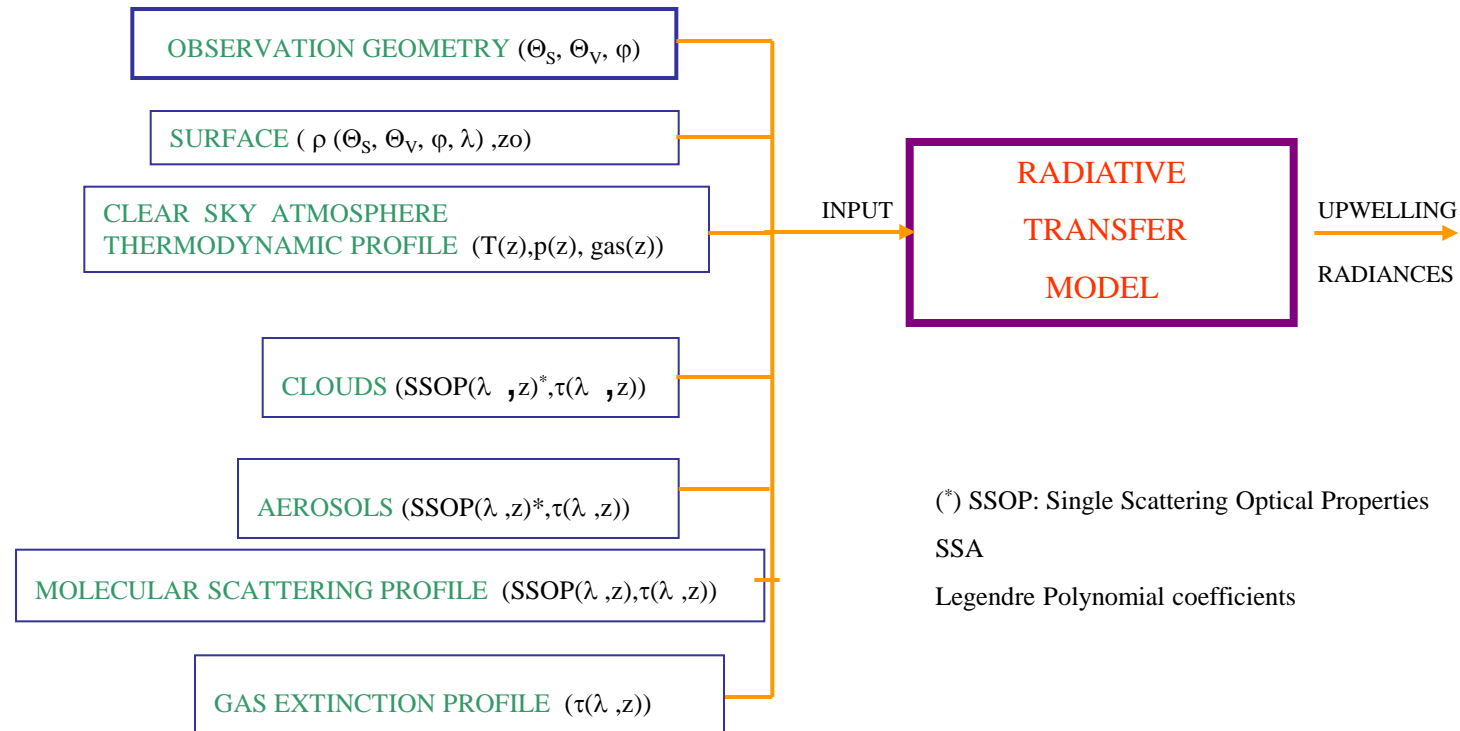
Radiative Transfer Modeling: Concepts/Definitions

- **Radiative Transfer Equation Solver:** Risolve l'equazione del trasporto radiativo (nel caso di multiple scattering): Es. DISORT
- **Radiative Transfer Model:** Simula il campo di radianza/flusso data una determinata scena geofisica: Es SCIATRAN
- **Instrument Simulator:** Simula il comportamento di uno o piu' strumenti esistenti o in fase di progettazione: Es. RTTOV, EarthCARE end-to-end Simulator
- **Radiative Transfer Tools:** permettono il calcolo delle proprieta' ottiche (una tantum->LUT o on-line). Calcolo delle proprieta' ottiche di singolo scattering (es: MIEV0, T-Matrix), Calcolo dei correlated k-band coefficients, calcolo della BRDF

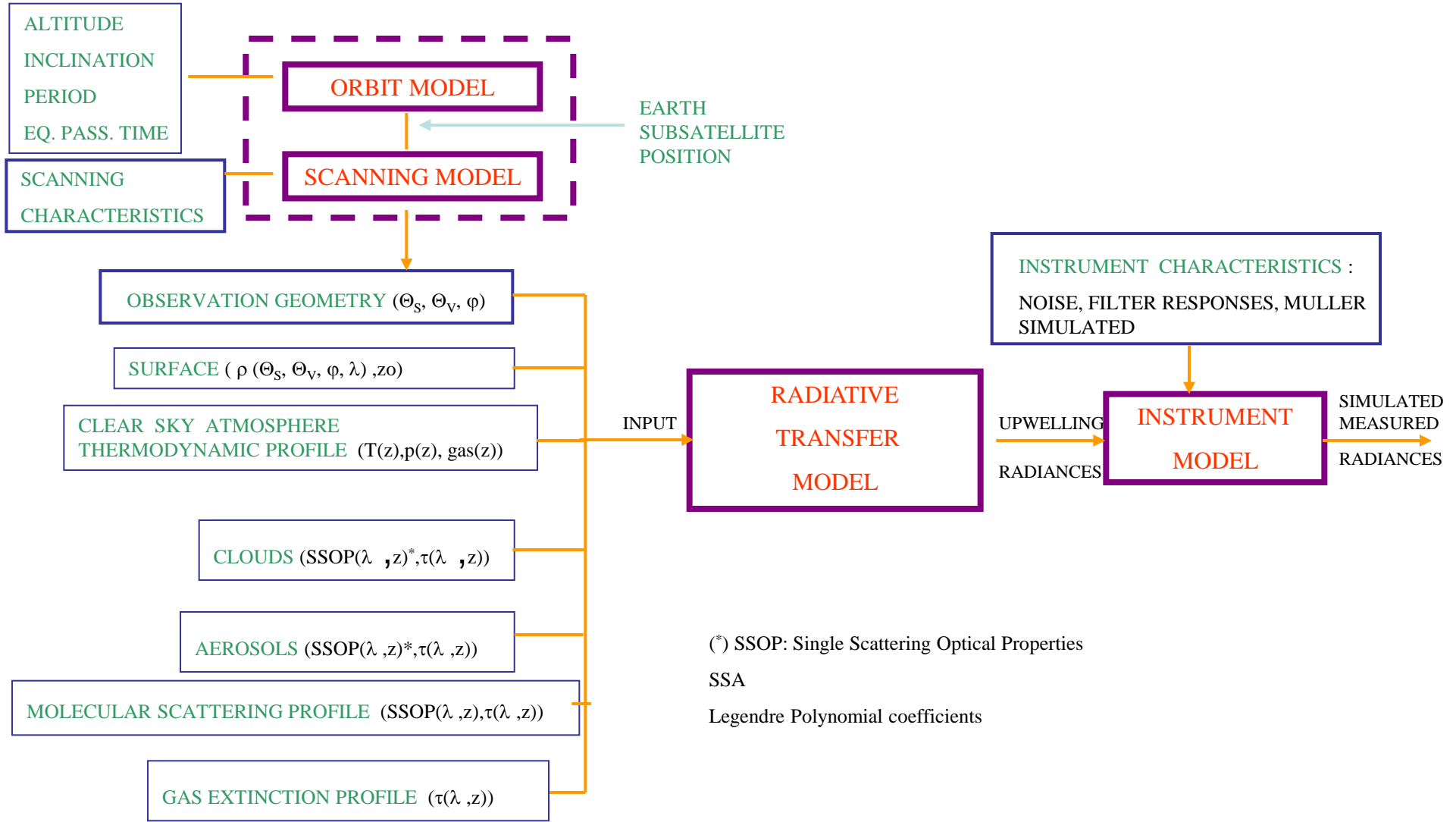
Radiative Transfer Equation Solver



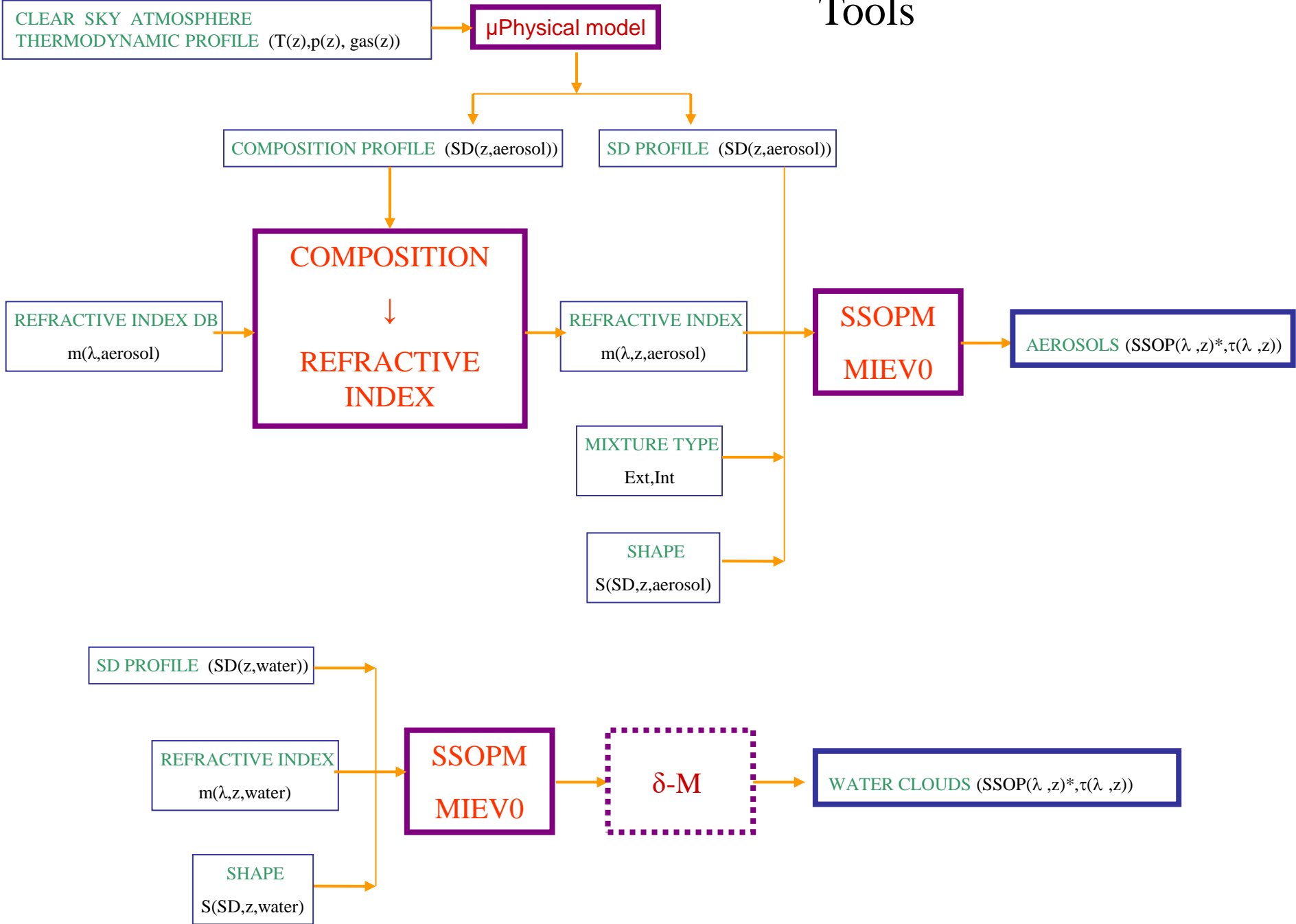
RADIATIVE TRANSFER MODEL



INSTRUMENT SIMULATOR



Tools



Radiative transfer modeling

- Model type/purpose: simulazione di strumenti, calcolo di flussi radiativi (per es all'interno di modelli di previsione numerica)
- Spectral range/integration
- Angular integration
- Polarization
- Physical Processes/level of parametrization
- SurfaceAtmosphere Coupling
- Geometry: plane parallel, spherical, 3D.
- Input (e.g. user defined)
- Output
- User friendly
- Examples & Libraries
- Computational efficiency

Radiative transfer modeling

https://en.wikipedia.org/wiki/Atmospheric_radiative_transfer_codes

1 problem/equation more than 40 different models?

- Model type/purpose: e.g. simulation of instruments, computation of radiative fluxes for radiative budget in numerical circulation/climate models, etc.
- Spectral range/integration
- Angular integration
- Polarization
- Physical Processes/level of parametrization
- SurfaceAtmosphere Coupling
- Geometry: plane parallel, spherical, 3D.
- Input (e.g. user defined)
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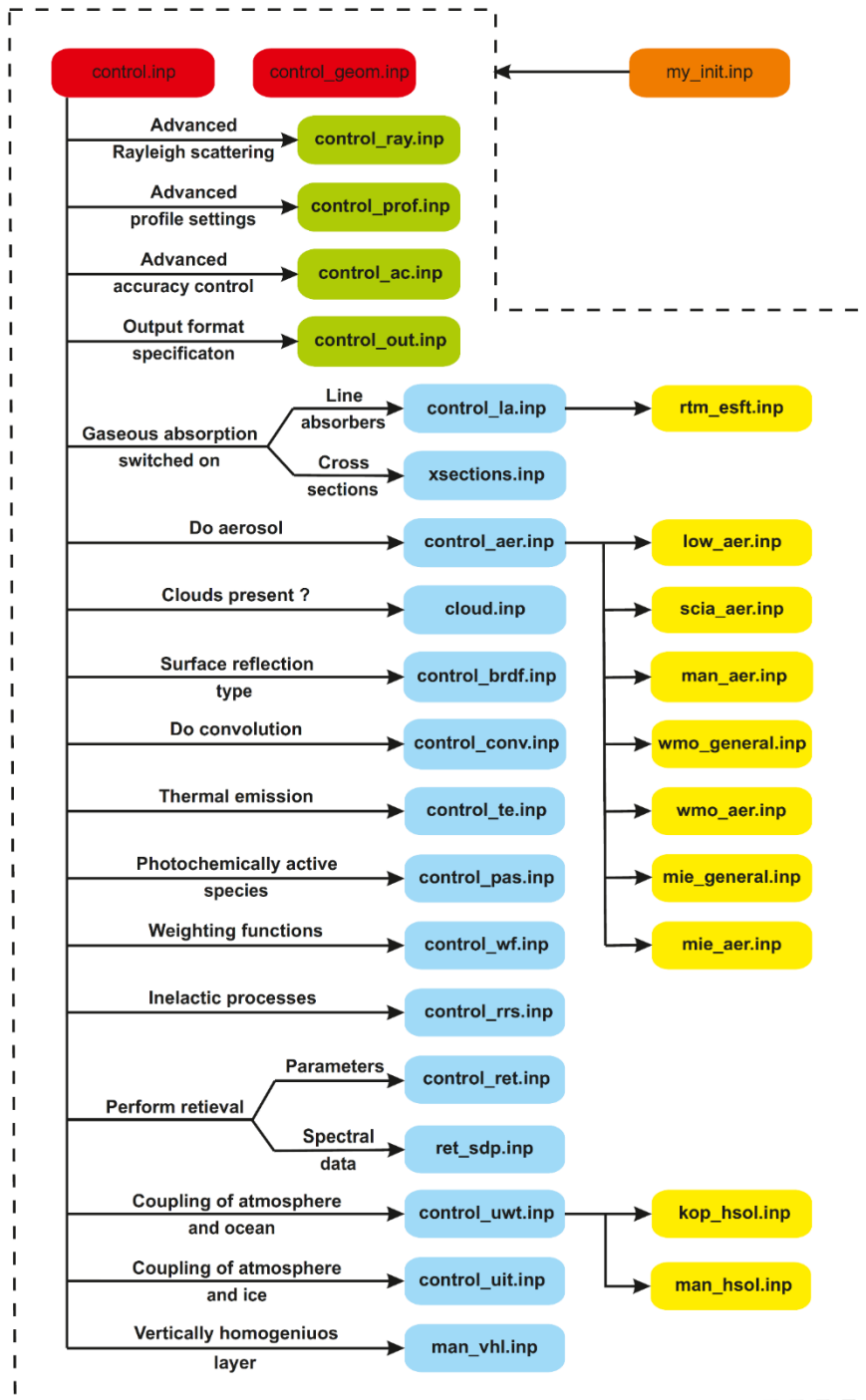
Use the model optimized for your problem/resources

Comments on RTM

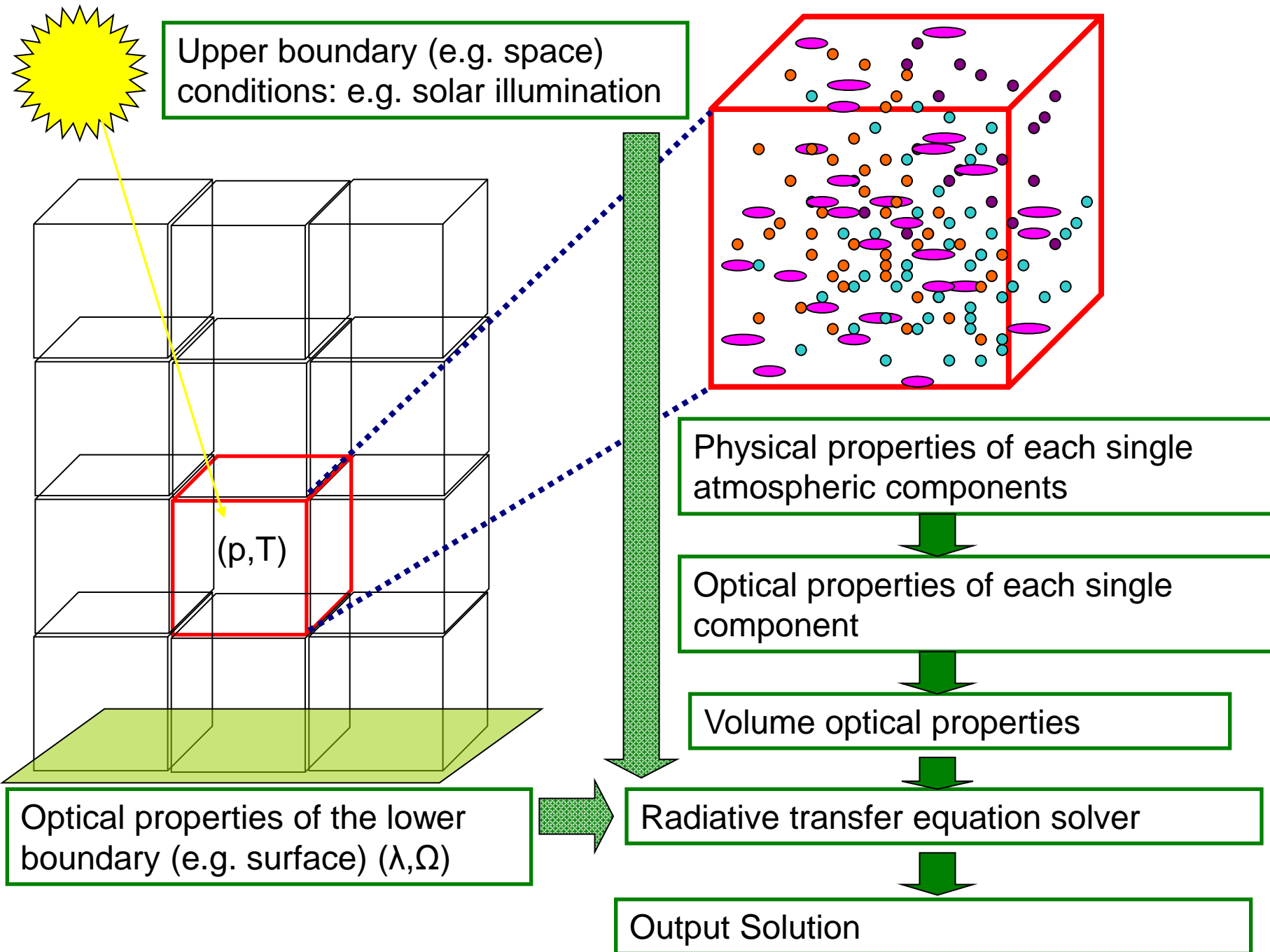
- Completeness of the represented processes. (e.g. type of absorption band model, numerical solution of the multiple scattering)
- Assumptions (e.g. Lambertian surface representation)
- Internal database (e.g. angular representation of single scattering properties)

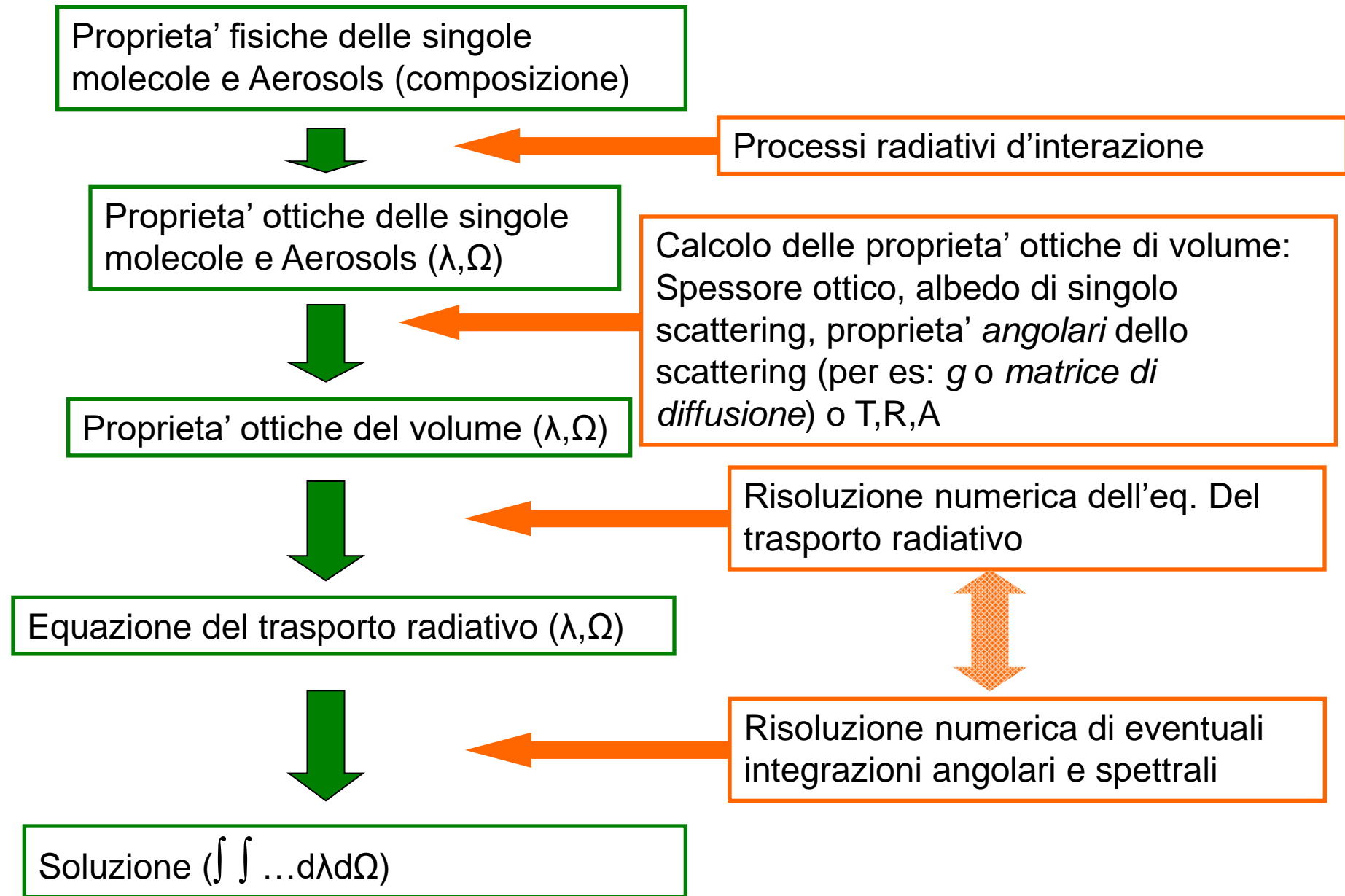
Hot issues

- Polarization
- Non-sphericity+multiple scattering
- Inelastic processes (Raman, Fluorescence)
- Fully coupled Atmosphere-Surface (e.g. Ocean)



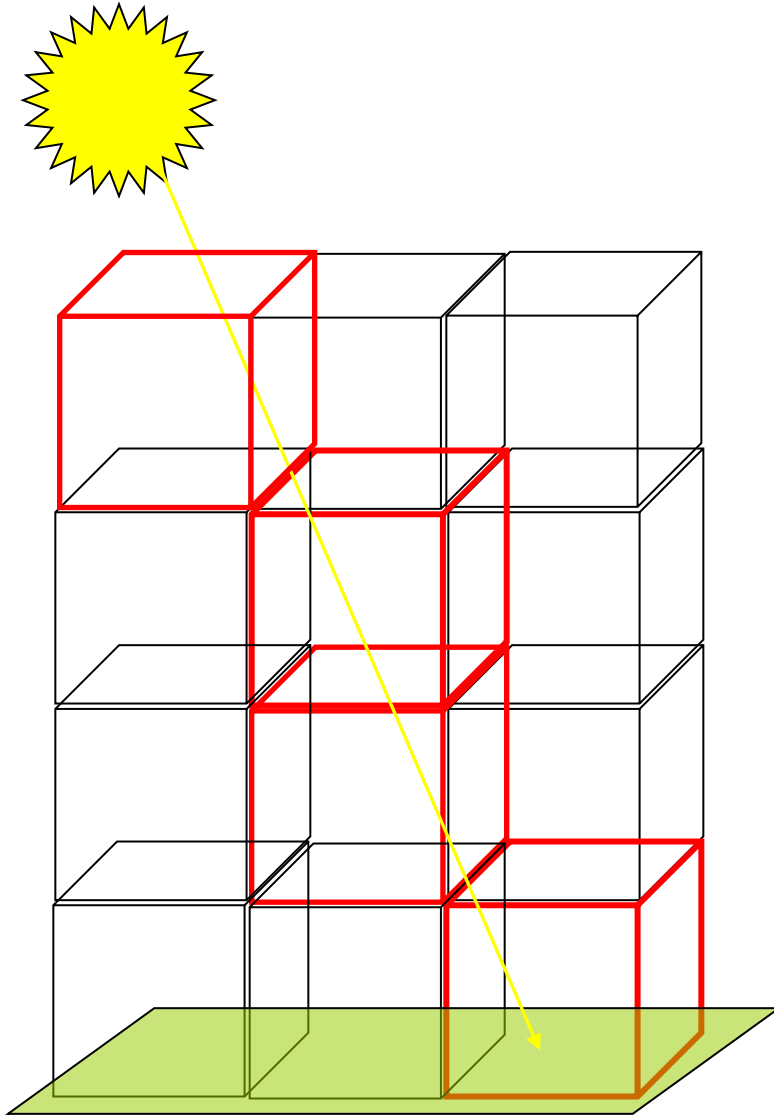
SCIATRAN control input files: From the geophysical scene to the simulated radiance (measurement)





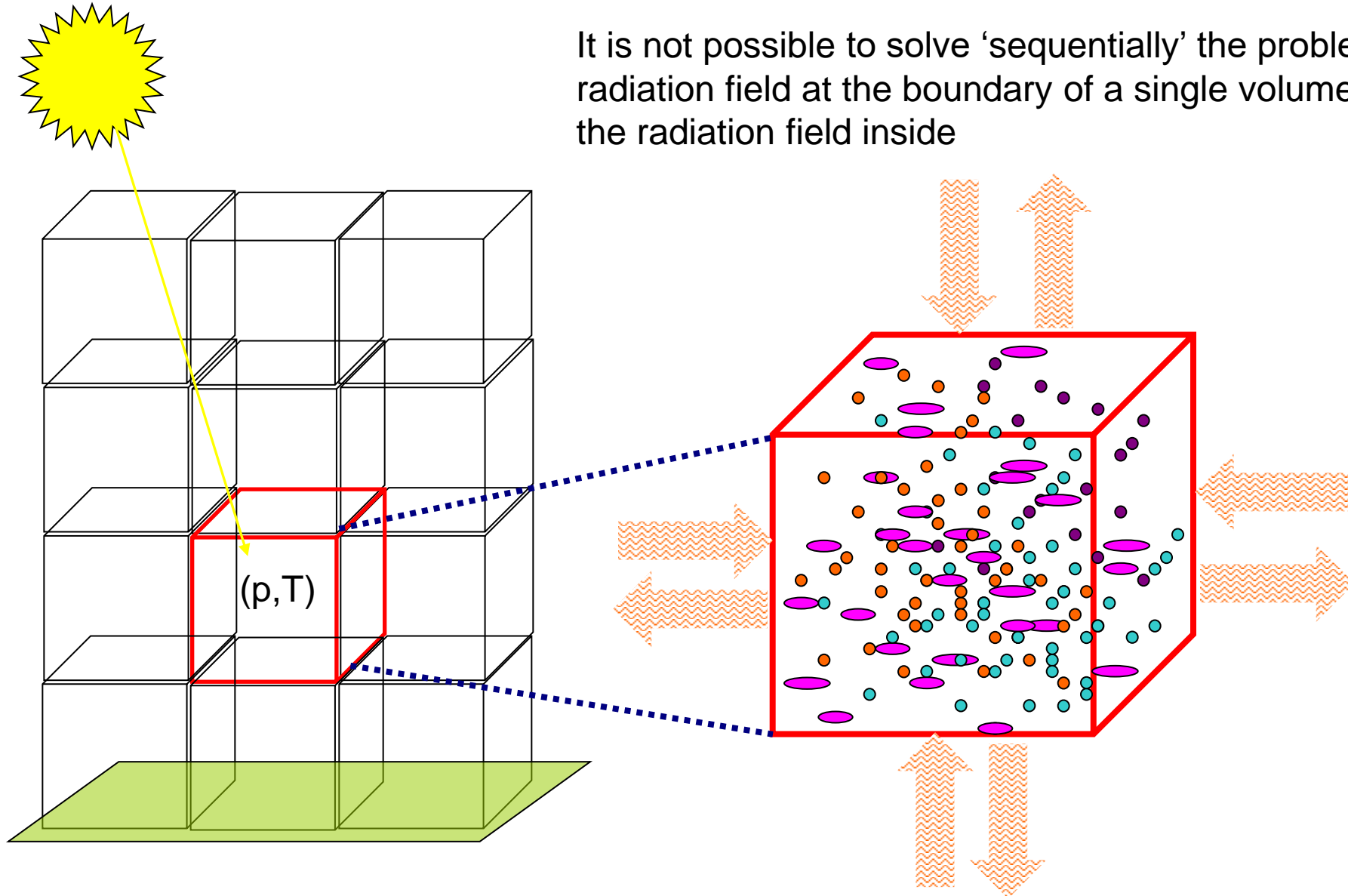
Radiative Transfer Model in Single Elastic (Scattering/Reflection) Processes Assumption

The problem can be solved sequentially



Radiative Transfer Model in Multiple Elastic (Scattering/Reflection) Processes Assumption

It is not possible to solve 'sequentially' the problem because the radiation field at the boundary of a single volume depends from the radiation field inside



Multiple Scattering Computational Techniques

1. **Discrete Ordinates:** Write a system of equations and linearize it to search the solution as an estimation of eigenvalues
2. **Doubling or Adding Principle:** If reflection and transmission is known for each of two layers, the reflection and transmission from the combined layer can be obtained by computing the successive reflections back and forth between the two layers. If the two layers are chosen to be identical, the results for a thick homogenous layer can be built up rapidly in a geometric (doubling) manner.
3. **Successive Orders of Scattering Principle:** Intensity is computed individually for photons scattered once, twice, three times, etc. with the total intensity obtained as the sum over all orders. If the intensity is expanded in a Fourier series, the high frequency terms arise from photons scattered a small number of times. Therefore, most Fourier terms can be obtained with some accuracy by computing a few orders of scattering.
4. **Iteration of Formal Solution** Direct solution of integral over source function by dividing atmosphere into layers with small optical thickness.
5. **Invariant Imbedding** Differential Equations are developed which give the change of reflection and transmission matrices when an optically thin layer is added to the atmosphere. It is a special case of the Doubling or Adding technique.
6. **Method of X and Y Functions** Involves the determination of integral equations for functions which depend upon only one angle and are directly related to Reflection and Transmission matrices. The integral equations need to be solved numerically. The integral equations are completely specified by a character function depending on the particular phase function. This method is due to Chandrasekhar.
7. **Spherical Harmonic Method** Intensity is immediately expanded into a finite number of spherical harmonics and then the Phase Function is expanded in Legendre polynomials similar to the Discrete Ordinate method.
8. **Expansion in Eigenfunctions** Standard technique for solving differential equations. Find homogenous solution and particular solution. Apply boundary condition. Direct application to complete RTE is ponderous. Discrete Ordinates technique depends on this approach for solving discretized set of equations.
9. **Monte Carlo Method** Scattering of an individual photon can be considered to be a stochastic process, with the Phase Function being the probability density function for scattering at a given angle. Photons are allowed to play a game of chance in a computer and by recording the history of a sufficient number of photons, the radiation field can in principle be determined to an arbitrary accuracy. The basic simplicity of this method allows great flexibility, and hence it can be applied to complicated problems which would be virtually insoluble by other methods.

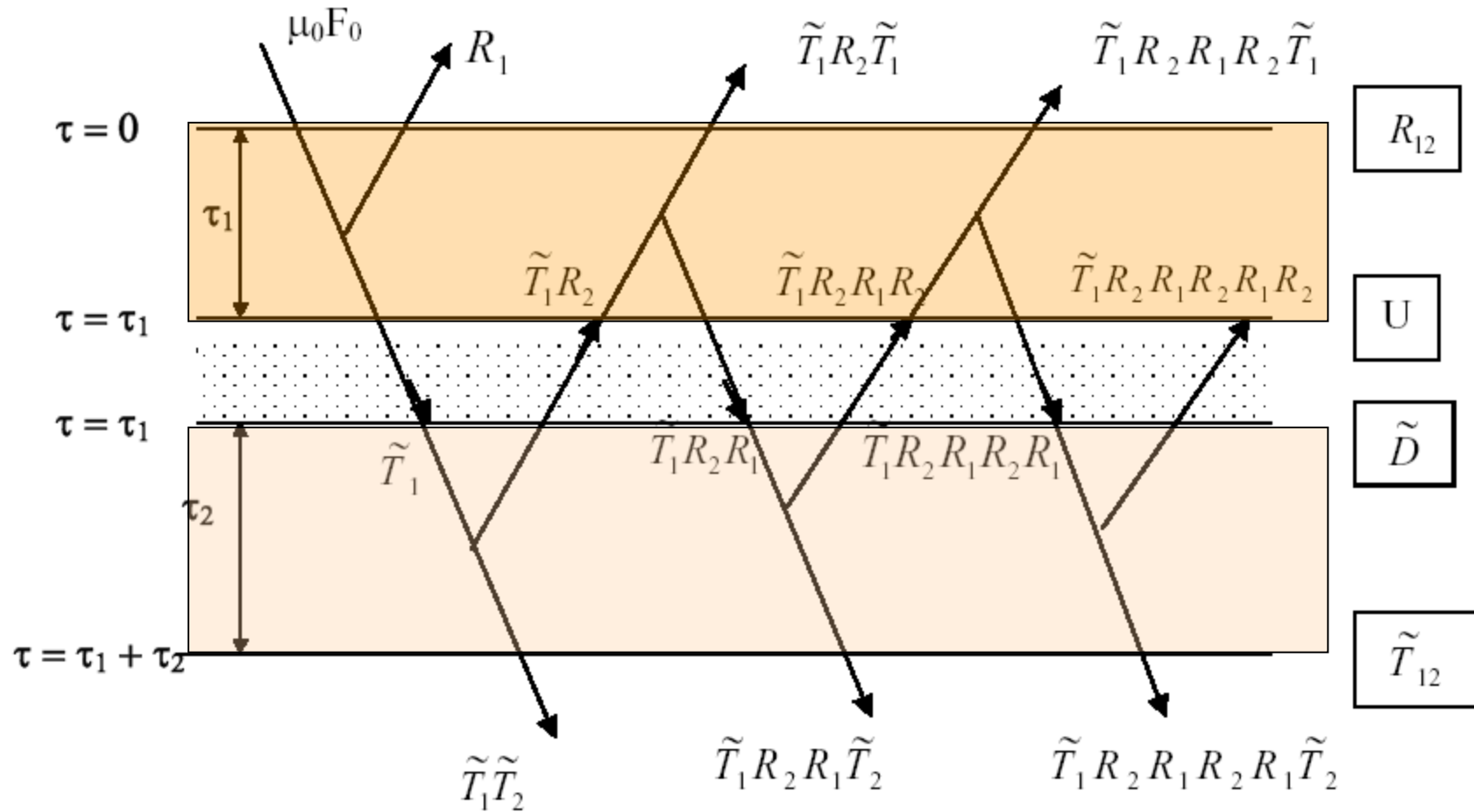
Adding and Doubling

- Hyp: per uno strato otticamente fino so calcolare la trasmittanza e riflettanza a partire delle proprietà ottiche.
- Divido il mio mezzo in strati tali che sono nelle condizioni di singolo scattering
- Utilizzando l'espressione:

$$\sum_{m=0}^{\infty} z^m = \frac{1}{1-z} \quad (|z| < 1).$$

Calcolo l'effetto combinato di piu' strati ovvero riflettanza e trasmittanza per strati otticamente densi.

DOUBLING OR ADDING METHOD



Si definisce per la trasmissione diffusa e per la riflessione:

$$Q = R_1 R_2$$

$$S = Q(1 - Q)^{-1}$$

$$D = T_1 + ST_1 + S \exp(-\tau_1 / \mu_0)$$

$$U = R_2 D + R_2 \exp(-\tau_1 / \mu_0)$$

$$R_{12} = R_1 + \exp(-\tau_1 / \mu)U + T_1 U$$

$$T_{12} = \exp(-\tau_2 / \mu)D + T_2 \exp(-\tau_1 / \mu_0) + T_2 D$$

Un prodotto $R_1 R_2$ implica:

$$R_1 R_2 = 2 \int_0^1 R_1(\mu, \mu') R_2(\mu', \mu_0) \mu' d\mu'$$

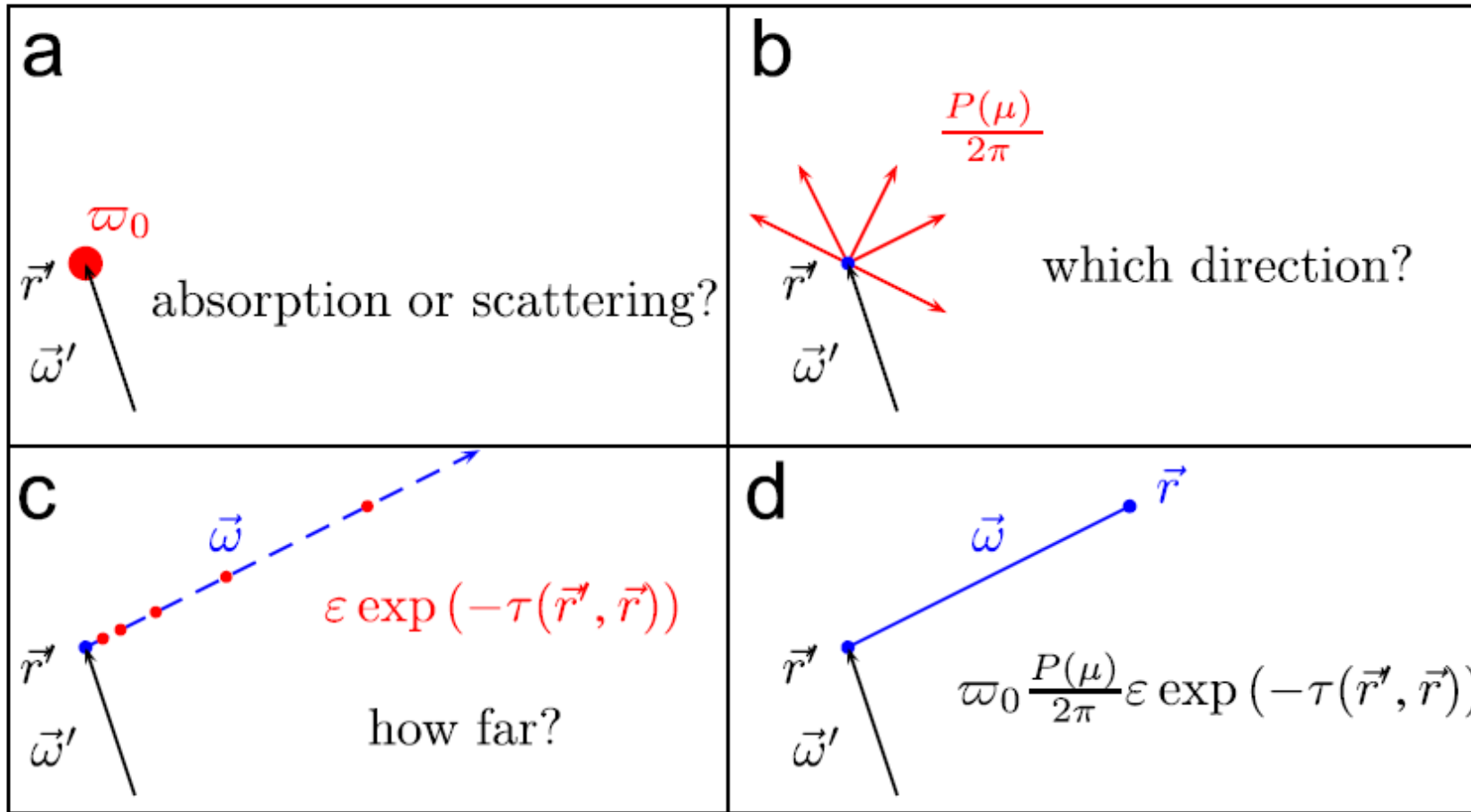
Monte-Carlo: Basics

0) Caratterizzo ogni volume/strato del mio mezzo con Riflettanza+Assorbanza+Trasmittanza=1 + Matrice di Scattering

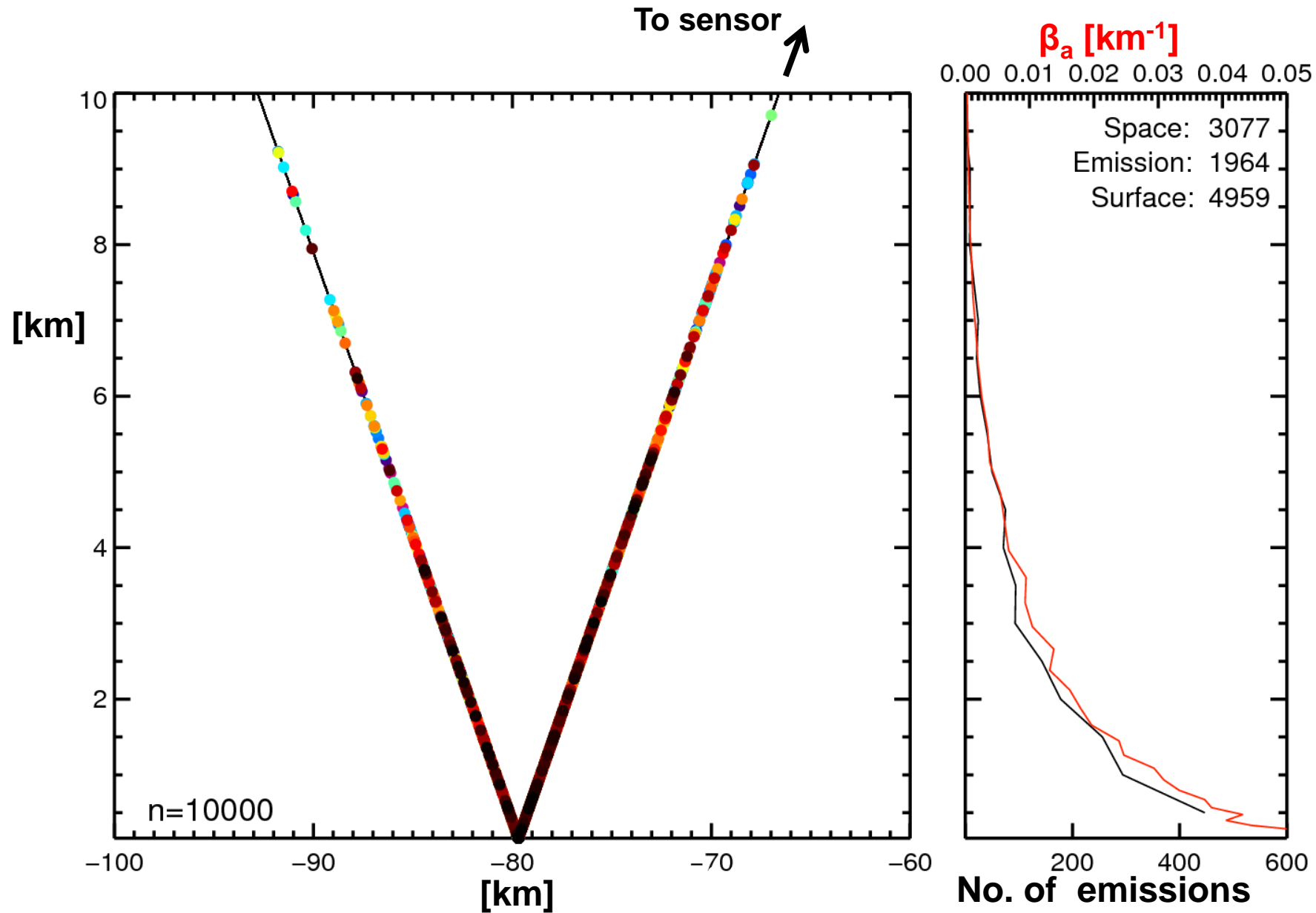


- 1) 'Lancio' un fotone dalla sorgente sul primo volume del cammino. Con un numero Random (0,1) vedo se e' Trasmesso (prosegue nel prossimo volume secondo la direzione originale) Assorbito (fine corsa) o Scatterato.
- 2) Se scatterato utilizzo la funzione di Fase cumulata [0,1] per stabilire in che direzione viene scatterato

Monte-Carlo: 2



Emission regime->Reverse Monte-Carlo: 19 GHz v-pol



Successive order of scattering

1. Faccio il calcolo del trasferimento radiativo nell'ipotesi di singolo scattering per es in un caso in cui il sole sia la sorgente.
2. Salvo sia la soluzione I_n che il campo di intensità scatterata.
3. 'Spengo' la sorgente ed utilizzo come sorgente il campo di radiazione scatterata nello step precedente I_{n-1}
4. Ripeto da 2 fino a che per es il contributo alla soluzione sia trascurabile

Useful links

On-line simulations

<https://psg.gsfc.nasa.gov/>

<https://satcorps.larc.nasa.gov/jin/coart.html>

http://modtran.spectral.com/modtran_home

Codes

<https://github.com/paulricchiazzi/SBDART>

<https://nwp-saf.eumetsat.int/site/software/rttov/>

<https://salsa.umd.edu/6spage.html>

en.wikipedia.org/wiki/Atmospheric_radiative_transfer_codes

Tools

http://omlc.ogi.edu/calc/mie_calc.html Interactive Mie Scattering Calculator

<https://www.spectraplot.com/>

<http://eodg.atm.ox.ac.uk/ATLA>

Data base

<https://hitran.org/>

History

oceanopticsbook.info/packages/iws_l2h/conversion/files/Mobley_EvolutionRTT_draft.pdf

Limits/Assumptions www.youtube.com/watch?v=hjKJyn_uoIE



THANKS!

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3.1: “Fund for the realisation of an integrated system of research and innovation infrastructures”

